TECHNICAL REPORT
TR-NAVFAC-EXWC-PW-1406
APRIL 2014

BUILDING INTEGRATED PHOTOVOLTAIC (PV) ROOFS FOR SUSTAINABILITY AND ENERGY EFFICIENCY

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
21 APR 2014

2. REPORT TYPE
Technical Report

3. DATES COVERED
00-03-2009 to 00-04-2014

4. TITLE AND SUBTITLE
Building Integrated Photovoltaic (BIPV) Roofs for Sustainability and Energy Efficiency

5a. CONTRACT NUMBER
N62473-06-D-3009

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
EW-200813

5e. TASK NUMBER
DO-17

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NAVFAC Engineering and Expeditionary Warfare Center,1000 23rd Avenue,Port Hueneme,CA,93043

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-NAVFAC-EXWC-PW-1406

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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building integrated photovoltaic roof; PV; renewable energy; rooftop PV

<table>
<tr><td colspan="3">16. SECURITY CLASSIFICATION OF:</td><td rowspan="2">17. LIMITATION OF ABSTRACT
Public Release</td><td rowspan="2">18. NUMBER OF PAGES
50</td><td rowspan="2">19a. NAME OF RESPONSIBLE PERSON</td></tr>
<tr><td>a. REPORT
unclassified</td><td>b. ABSTRACT
unclassified</td><td>c. THIS PAGE
unclassified</td></tr>
</table>

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Energy and Water

ESTCP Number: EW-200813

April 2014

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
21-04-2014	Technical Report	March 2009 – April 2014

4. TITLE AND SUBTITLE
Building Integrated Photovoltaic (BIPV) Roofs for Sustainability and Energy Efficiency

5a. CONTRACT NUMBER
N62473-06-D-3009

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5d. PROJECT NUMBER
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5e. TASK NUMBER
DO-17

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
TR-NAVFAC EXWC-PW-1406

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NAVFAC EXWC, 1100 23rd Avenue, Port Hueneme 93043

10. SPONSOR/MONITOR'S ACRONYM(S)
Naval Facilities Engineering and Expeditionary Warfare Center

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Peter Ly
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	50	**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U			805-982-1367

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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ACKNOWLEDGEMENTS

The authors would like to thank the Environmental Security Technology Certification Program in supporting this study, with special thanks to Dr. Jeffrey Marqusee and Dr. James Galvin. The authors would also like to especially thank Navy and Marine Corps personnel (Ron Durfey, Michael Boyd, Karl Bryan, Michael Oliver, Kevin Evans, Derek Briggs, Bill Nutting, John Dunbar, Rudy Liporada, Fred Speece, and Karl Jacobs), Air Force personnel (Garland Scott, AJ Muhs, and Francisco Pardieu), General Services Administration personnel (Roman Piaskoski, Dale Cameron, and Paul Needham), and Matthew Brito from Sandia National Lab for their collaboration/support with site visits, data collection, and information sharing. In addition, thanks to Timothy Murph of Pacific Solar Technologies and Tim Kraft, formerly of Uni-Solar, in answering technical questions related to BIPV roof maintenance and repair.

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ABBREVIATIONS & ACRONYMS

A/C	Air Conditioning
a-Si	Amorphous Silicon
AC	Alternating Current
AFB	Air Force Base
AHU	Air Handing Unit
APS	Arizona Public Service
ASTM	American Society for Testing and Materials
AZ	Arizona
BIPV	Building Integrated Photovoltaic
BTU	British Thermal Units
C	Celsius
CA	California
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Di-Selenide
DC	Direct Current
DoD	Department of Defense
DOE	Department of Energy
EMS	Engineered Management System
EO	Executive Order
EXWC	Engineering & Expeditionary Warfare Center
ESPC	Energy Savings Performance Contract
ESTCP	Environmental Security Technology Certification Program
EUL	Enhanced Use Lease
FEAD	Facilities and Engineering Acquisition Division
FCI	Flashing Condition Index
FL	Florida
FY	Fiscal Year
HVAC	Heating, Ventilation, and Air Conditioning
ITC	Investment Tax Credit
kW	Kilowatt

kWh	Kilowatt-Hour
LBNL	Lawrence Berkeley National Lab
LEED-NC	Leadership in Energy & Environmental Design for New Construction
M&V	Measurement and Verification
MCAS	Marine Corps Air Station
MCI	Membrane Condition Index
MD	Machine Direction
MILCON	Military Construction
NAVFAC	Naval Facilities Engineering Command
NAS	Naval Air Station
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
PPA	Power Purchase Agreement
PV	Photovoltaic
PVC	Polyvinyl Chloride
PVL	Photovoltaic Laminate
REM	Renewable Energy Management
RCI	Roof Condition Index
ROICC	Resident Officer in Charge of Construction
SIR	Savings to Investment Ratio
SRM	Sustainment, Restoration and Modernization
STC	Standard Test Conditions
TPO	Thermoplastic Olefin
UFGS	Unified Facilities Guide Specification
VA	Virginia
W	Watts
WA	Washington

EXECUTIVE SUMMARY

Conventional rooftop solar photovoltaic (PV) systems increase roof load, can compromise roof integrity and void the warranty. A building integrated photovoltaic (BIPV) roof can function as a heat reflective roof, provide renewable energy, and can potentially cost less than a conventional roof and PV system installed separately. The form of BIPV roof in this study used amorphous silicon (a-Si) PV modules adhered to a reflective polyvinyl-chloride (PVC) membrane, which is thermally bonded to an ENERGY STAR-rated PVC roof membrane. Conduit is laid between insulation boards. The objectives were to study BIPV roof performance as both PV and roofing systems; focused on an existing BIPV roof at Site I (Luke AFB) and new systems at Site II (NAS Patuxent River) and Site III (MCAS Yuma); evaluated roof integrity, reflectivity and temperature and PV output. Operations and maintenance requirements and other BIPV roofs were qualitatively evaluated.

Roof integrity evaluated using the ROOFER Engineered Management System showed that Sites I and III both had little change in roof condition indices, whereas Site II had a significant reduction in membrane condition index due to mold. Note that ROOFER does not account for PV components. ASTM D 4434 tests on field weathered PVC samples from two parts of the Site III system indicated that different environmental conditions did not definitively impact longevity.

Roof reflectivity was spot measured during the three-year study. Sites I and III had up to a 29% reduction in reflectivity due to desert soiling. Site II had a 24% reduction due to mold. Desert soiling may be removed by rain, but the mold growth will only worsen. While the data show an overall decrease of reflectivity, they were still better than that of many conventional, dark roofs.

Roof temperature was studied extensively at Site III. Data shows that the BIPV roof reduces heat gain. However, the poor building envelope at the attic and malfunctions with the air conditioning equipment made it impossible to correlate the facility energy use to roof temperature. Computer models simulated the BIPV impact to a prototypical office building as if it was in Phoenix, AZ; San Diego, CA; Seattle, WA; Norfolk, VA; Jacksonville, FL. These sites were chosen to represent different climates and common DoD locations within the United States. The simulations showed that BIPV roofs can result in a net positive energy savings at each location.

Actual vs. expected energy output was used to assess PV performance. Site I had only two months of data due to problems with the manufacturer's monitoring system and it indicated that the PV system met 80% of the expected output and was likely impacted by desert soiling. Site II often experienced cloudy weather, but performed roughly 30% better than expected and was likely because a-Si PV works relatively well under diffused sunlight. Site III suffered from desert soiling, but not to the same extent as Site I and was likely due to the facility's small size and simpler roof design. Data shows that the Site III BIPV roof has a relatively steady power conversion efficiency and met renewable energy generation expectations.

There were at least three BIPV roofs that experienced failed PV adhesives. The manufacturer applied a surface tape, but parts did not endure and caused other problems. A few sites had problems with occasional pin-size holes. The recommended repair procedure required a small flame, but one site lacked qualified, local personnel to perform it. Mold was a problem on several BIPV roofs in coastal/humid locations, but attempting to remove it would likely cause more damage than leaving it alone. Evidence of water ponding was found in several locations

and indicates a poorly designed and/or poorly installed BIPV system or problems with the previous roof that were not resolved prior to BIPV roof installation.

Cost effectiveness is best compared to conventional roofs and rooftop PV systems. Roofing costs vary most based on type and quality, so a $5-$20 per square foot range was used. *California Solar Statistics* shows that the installed cost of PV was roughly $7.5-$10/Watt (W) in 2008, the year the BIPV contract was awarded, and $4-$7.5/W in 2012 and was mainly due to the price of crystalline PV modules. Unfortunately, a-Si PV modules experienced a smaller price reduction.

Table-ES1: Actual BIPV roof costs compared to estimated 2012 capital costs for conventional roofs and PV systems.

Location	BIPV Cost at time of Award	Conventional Roof @ $5/sq.ft. and PV @ $4/W	Conventional Roof @ $5/sq.ft. and PV @ $7.5/W	Conventional Roof @ $20/sq.ft. and PV @ $4/W	Conventional Roof @ $20/sq.ft. and PV @ $7.5/W
Site I (Luke AFB)	~$6M (2005)	$2.2M	$3.5M	$4.4M	$5.7M
Site II (Patuxent River)	$363K w/ roof repairs; $332K w/o	$188K	$282K	$428K	$522K
Site III (MCAS Yuma)	$254K w/o rebate	$129K	$201K	$268K	$340K

The BIPV roof type reported here is no longer available due to adhesion problems and better design practices, but adhered PV approaches are still being used and often considered to minimize roof penetrations or weight loading. In some systems, thermoplastic-olefin replaced PVC to be more adhesive-compatible; other flexible PV materials have been used because of higher conversion efficiencies; conduit became surface-mounted to be more firefighter friendly.

In spite of the improvements, the problems identified by this study may still occur with new adhered systems. The National Electric Code addresses some PV safety concerns, but fire and firefighter safety standards still need development, so consult with base safety personnel before and during the design phase. Improper water drainage can reduce roof longevity and may be remedied with a thorough review of the design by a roofing specialist, using a rigorous quality assurance/control plan, and performing a BIPV roof assessment before the workmanship warranty expires. In the case of a retrofit, problems with the existing roof need to be remedied prior to BIPV roof installation. Mold growth can reduce roof reflectivity even if it does not reduce roof longevity so ensure that the manufacturer and installer warranties address this aspect. PV adhesives may still fail and improperly tested solutions may worsen the situation by making other remedies more difficult to implement. A comprehensive warranty may mitigate risk, but is ineffective if the warrantor goes out of business as was the case during this study. Third-party solutions may be available, but may void any remaining warranties. Various acquisition vehicles can mitigate the technical risks, but contracting complexity, costs, and risk must be balanced.

The concerns with BIPV roofs can be mitigated, so DoD personnel in charge of rooftop solar projects need to determine whether or not the cost and benefits outweigh those of conventional rooftop PV systems. It is recommended that DoD personnel interested in BIPV roofs be aware of the issues, consult with a roofing specialist and obtain training and/or consultation from experienced personnel prior to the design and construction phases. It is recommended that DoD maintain a list of adhered PV systems and their basic PV and roof components and survey a sample set every few years to identify performance/durability trends.

1.0 INTRODUCTION

1.1 BACKGROUND

Renewable energy systems are typically long term investments and require large areas of land to benefit from economies of scale. Unused roof space has contributed to the adoption of rooftop solar photovoltaic (PV) systems. However, this has led to concerns about increasing roof loading, compromising roof integrity and violating the warranty since the roof and PV systems are often provided by different companies.

One solution is to use building integrated photovoltaic (BIPV) roofs. In one form, thin-film PV modules are factory-adhered to a reflective polyvinyl-chloride (PVC) carrier sheet, which is then field-bonded to an ENERGY STAR-rated PVC roof membrane. Replacing an old, inefficient roof system with new insulation, an ENERGY STAR-rated roof membrane, and an integrated photovoltaic system is an approach that may yield a positive return on investment. Also, if BIPV roof installation coincides with a re-roofing effort, the avoided re-roofing cost may be used to fund the installation of a BIPV roof, which will significantly shorten the payback period and provide immediate environmental benefits.

Department of Defense (DoD)-wide implementation of this technology has the potential to increase energy security, generate renewable energy credits to meet energy goals, decrease energy consumption by reducing building interior cooling loads, reduce greenhouse gas emissions, improve air quality, and lower building-life-cycle-costs.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective was to demonstrate and validate whether BIPV roofs can endure weather conditions as well as conventional roofs, and to verify whether an integrated rooftop PV system can result in an energy efficient roof. This project also investigated whether a BIPV roof system is structurally sound, how the system is expected to perform over 20 years under normal operation, and its effectiveness in providing on-site renewable energy generation. Implementation guidance was provided to help with future use of this technology.

1.3 REGULATORY DRIVERS

Sustainment, restoration and modernization (SRM) funds are generally allocated to high priority projects first. As facilities go unmaintained, energy efficiency is reduced and maintenance and energy costs will increase. To mitigate future maintenance and environmental problems, DoD has policies in place for attaining Leadership in Energy & Environmental Design for New Construction (LEED-NC) certification. In addition, the Energy Independence and Security Act of 2007 directed DoD to implement green building technologies and reduce fossil fuel requirements of our buildings. New technologies need to be evaluated and design guidelines need to be created/updated for proper implementation. Furthermore, both the Energy Policy Act of 2005 and Executive Order (EO) 13423 mandate a reduction in building-energy intensity by 30% by Fiscal Year (FY) 2015. The Defense Authorization Act for Fiscal Year 2007 dictates that DoD services are to achieve 25% renewable energy usage by 2025. EO 13423 further requires that at least half of the required renewable energy consumed comes from projects placed in service after January 1, 1999.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Most PV systems are mounted on aluminum racks. These racking systems have been used on rooftop systems as well as on ground-mounted systems for many years. As the solar energy industry developed, new racking systems were invented for different roof types and for certain aesthetic features. These systems can be integrated with the roof by penetrating the roof to attach the racking system. Another method is to attach the PV modules to the roof using an adhesive. The use of adhesives reduces, if not eliminates, roof penetrations and works with a variety of roof types, but the PV module's mounting angle is restricted to the slope and orientation of the roof. A third type of BIPV system uses heat welding and adhesives to bond the PV modules to a membrane roof. The backing of the module is made of the same material as the roof, which allows for this method of PV integration. This also eliminates roof penetrations and is potentially more reliable than the adhesive-only approach, but is restricted to certain roofing materials.

Crystalline silicon based PV technology is currently the most commonly used. Several years ago, the increased demand of silicon from both the PV and the electronics industries resulted in a silicon shortage and an increase to the cost of PV modules. The shortage has since disappeared but may still return depending on market and supply changes.

Other PV materials, such as thin film PV, are also available. Different thin film materials have different properties, but in general, they are more flexible in building integrated applications than crystalline-based PV and use relatively little-to-no silicon. This factor helps drive the industry's interest in the technology. Copper indium gallium di-selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (a-Si) are the three most common thin film technologies available today.

The form of BIPV roof demonstrated in this ESTCP project utilizes a-Si PV laminates (PVLs) factory adhered to an ENERGY STAR qualified PVC carrier sheet. ENERGY STAR qualified roof products are basically more reflective than non-qualified products. The PVLs and PVC carrier sheet forms the BIPV panel (Figure-1). The edge seal from the adhesive used to bond the PVL to the PVC carrier sheet can be seen. The dark border of a PVL does not produce power and only surrounds a set of PV cells like a frame. Figure-2 is an example of a cross-section of the BIPV roof assembly. The conduit runs in between the insulation boards.

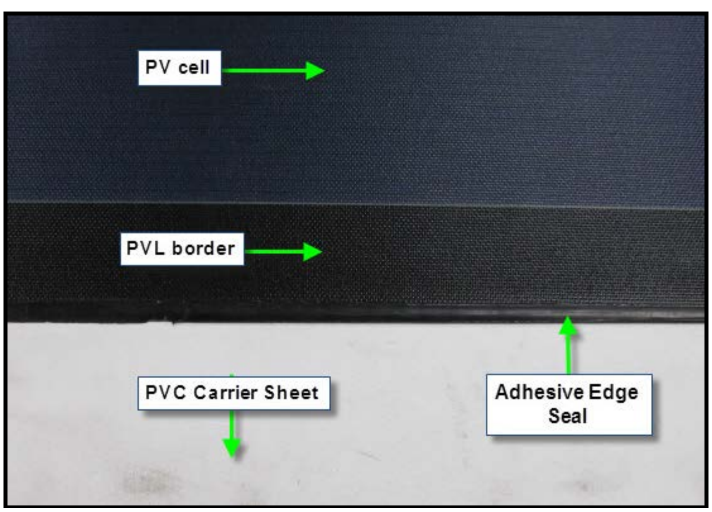

Figure-1: Close-up of the PVL and the PVC carrier sheet.

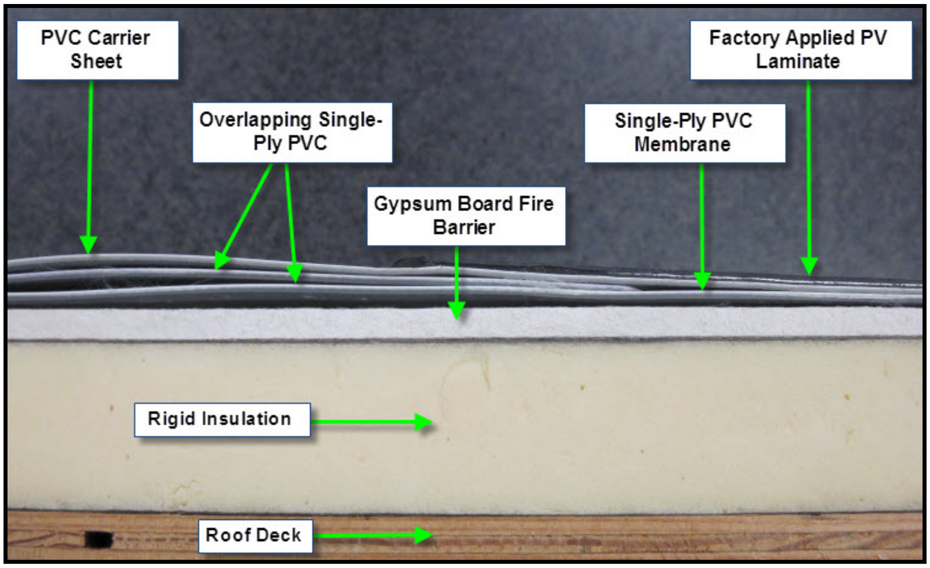

Figure-2: Cross-section of BIPV roof assembly without the conduit.

The conduit for the PV system and the roof insulation layer are first concurrently installed, followed by the installation of the PVC membrane layer. Mechanical fasteners, similar to the ones used in regular PVC roofs, hold the layers together. Then, the BIPV panels are connected to the conduit and finally heat welded to the PVC membrane to form an integrated roofing system. This design minimizes the concerns of exposed wiring and roof penetrations associated with the installation of some rooftop PV systems. If an existing roof is in good condition (e.g., no leaks or wet insulation, etc.), it is also possible to overlay the BIPV roof, from the insulation on up, on top of the existing roof. However, this may void the existing roof warranty, so the corresponding installer and manufacturer should be consulted prior to BIPV installation.

Figure-3 shows some mechanical fasteners that attach the PVC membrane to the gypsum board and insulation below. These particular fasteners are only used along the edges of the PVC sheet. To form a watertight roof, the sheets overlap so that the top sheet seals off the fasteners below it. The bottom of the overlapping PVC membrane sheet can also be seen in Figure 3.

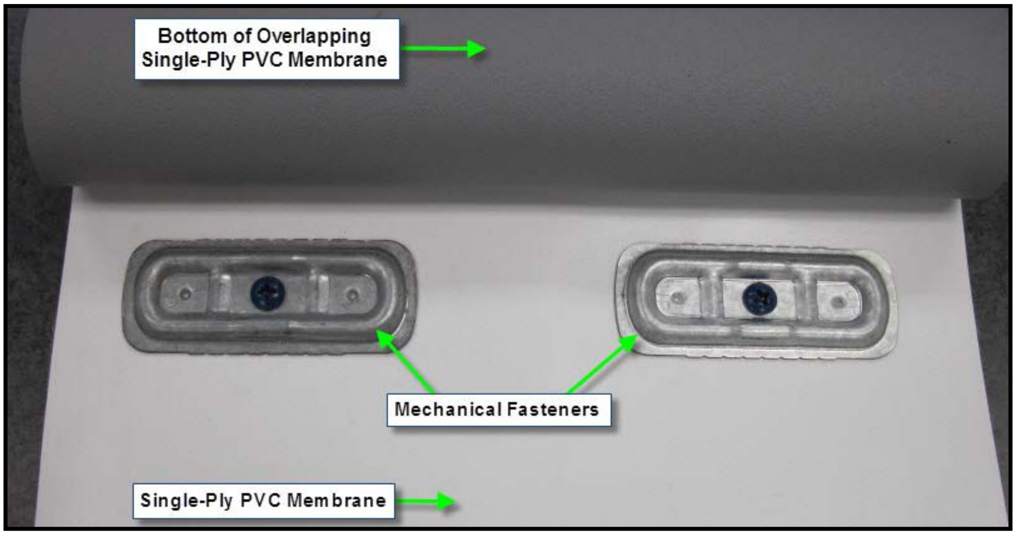

Figure-3: The mechanical fasteners holding down the single-ply PVC membrane.

Figure-4 shows two overlapping PVC membrane sheets and the seam from the heat welding used to form the bond between them. The PVC carrier sheet from the BIPV panel is attached to the PVC membrane using the same process. This completes how the BIPV roof was assembled.

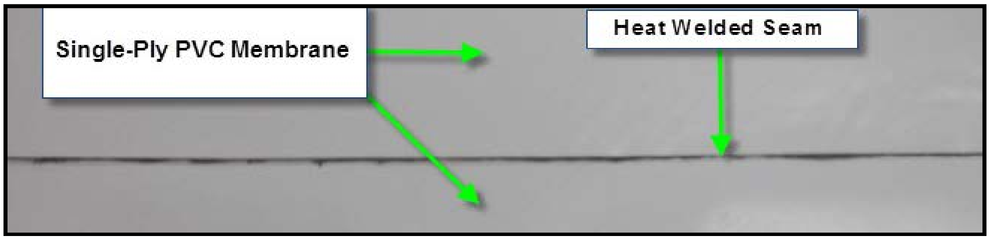

Figure-4: The overlapping area of single-ply PVC membrane under the BIPV panel.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Currently, a-Si thin-film PV material has lower conversion efficiencies than crystalline silicon PV. However, a-Si cells can be manufactured at lower temperatures and deposited on low-cost substrates. The less energy intensive manufacturing process means that it takes less time for an installed a-Si PV module to generate the energy it took to manufacture the module. Furthermore, a-Si PV performance is less sensitive to the solar angle and increasing temperature. This potentially makes a-Si PV more viable in BIPV applications since the installed angle is typically dependent upon the facility’s shape and the modules are mounted close to, if not flush against, the facility. However, the surface that a BIPV panel is mounted on needs to be rigid enough to maintain the slope needed for water drainage or will cause water ponding, which can damage the PV panel, PV attachment mechanism, roof membrane, and encourage microbial growth.

Some studies projected that thin film PV will cost less than crystalline PV and can perform competitively. The a-Si PV used in this demonstration has about a 6.3% solar-to-electric conversion efficiency at the module level (i.e., the entire PVL including the dark border). For comparison, commercially available thin film, CIGS PV manufacturers are boasting over 12% and crystalline PV panels are considered to have a good efficiency when over 15%, though 20% efficient crystalline panels are recently commercially available. Note that in this report, the use of PV module and PV panel have the same meaning, but BIPV panel specifically refers to the combination of the thin film PV modules and the PVC carrier sheet.

Reflective PVC roofs have the same disadvantage of any white roof, which is that its reflectivity can diminish due to the environment. Also, since PV modules are dark colored, this may cause heat gain and increase the facility's cooling requirement. In the case of a BIPV roof retrofit, if the pre-existing roof was not highly reflective, these factors may not have a net negative impact on the cooling load. Proper roof slope to avoid water ponding is also a concern, but is more significant in a single-ply PVC roof due to the fewer number of layers than a built-up roof. Another aspect is that PVC roof manufacturers typically provide 20-year warranties, whereas those for built-up or modified-bitumen roofs may exceed 20 years. In addition, the capital cost of a BIPV roof is substantially greater than that of a conventional roof due to the PV modules, but may cost less than a new roof with a conventional PV system. Finally, although PVC membranes and PV panels are typically free of maintenance, BIPV roof systems are relatively new, so the long term costs and maintenance requirements of the system is still uncertain.

3.0 PERFORMANCE OBJECTIVES

Roof integrity, renewable energy generation, changes to the building envelope, and operations and maintenance (O&M) requirements were the four primary categories of interest for this demonstration. These areas were investigated at a total of three demonstration sites. Site I was an existing BIPV roof. Roof integrity and the renewable energy generation capability were investigated at that site. Site II and III had new BIPV roofs installed. Roof integrity and the renewable energy generation capability were investigated at Site II and III, but Site III also included the investigation of the BIPV roof's effects on the air conditioning system. The performance objectives and results are summarized in Table-1.

Table-1: Performance objectives of the demonstration.

DEMONSTRATION PERFORMANCE OBJECTIVES				
Performance Objective	**Metric**	**Data Requirements**	**Success Criteria**	**Results**
Quantitative Performance Objectives				
Roof Integrity at all sites (*Facilities*)	Roof condition assessments resulting in an overall condition index	In-person survey and evaluation of roofs	Deterioration characteristics of BIPV roof meets or exceeds predictive life curve in ROOFER EMS	Unsuccessful due to poor design/installation decisions and mold growth. However, design issues can be remedied to successfully meet the performance objective.
Roof Integrity (*Facilities*)	ASTM D 4434 for PVC Roofs	Certified laboratory testing	ASTM test results are equal or better than industry reported results for average roof types	Inconclusive. The test results for the weathered PVC samples were mixed.
Renewable Energy Generation at all sites (*Energy*)	Energy produced by solar PV system compared to available solar insolation	Measurement of KWH produced and weather conditions, including horizontal solar insolation	Measured energy produced corresponds to estimated energy production based on system efficiency	Successful based on measured solar-to-electricity conversion efficiency.
Increased energy efficiency (*Energy and Facilities*)	Reflectivity of roof system	Measured reflectivity of roof membrane and PV panels	Composite reflectivity of the two materials does not fall below that of pre-existing roof	Successful based on the criteria during the study period, but roof reflectivity has degraded significantly.
Increased energy efficiency at Site III (*Energy*)	Reduction of air conditioning heating/cooling loads	Measurements and model of air conditioning energy consumption, heat flux through roof, temperatures of environment and roof system, and weather conditions	A net reduction in the air conditioning system's energy consumption	Inconclusive due to the poorly insulated attic space, which resulted in immeasurable changes to the air conditioning energy consumption. However, temperature sensors in the roof did indicate significant temperature decreases after the BIPV roof installation.
Qualitative Performance Objectives				
Operations and Maintenance at all sites (*Facilities*)	Roof condition assessments and local public works O&M duties	Feedback from the roof surveyors and facilities maintenance staff and O&M records	O&M level of effort for the BIPV roof does not exceed that for conventional roofs	Unsuccessful due to the maintenance needed on the PV portion of the roof.

Roof Integrity – ROOFER EMS

In-person surveys of the roof's condition were used to evaluate the integrity of roof at all three sites. The ROOFER Engineered Management System (EMS) provided the standard protocol that was followed. Each roof integrity survey resulted in a set of condition indices to be used as a quantitative metric. Indices are out of 100 and points are deducted based on the number and severity of problems that can be due to installation errors and/or damage. ROOFER EMS software uses built-in predictive life curves to project the life of a roof and lets the user determine if the roof will meet its rated life of 20 years. Using ROOFER EMS will help ensure that the results can be easily repeated by another organization and that the results are not questioned based on any usage of proprietary techniques, such as the manufacturer's performance evaluation package. Furthermore, since the evaluation of the roof integrity is limited to the period of the demonstration, it is ideal to use a standard roof evaluation procedure, which the facility manager can duplicate if any problems arise in the time following the demonstration period.

Based on the established criteria and evaluation methodology, the performance objective that evaluated roof integrity based on condition assessments was not met. The ROOFER EMS methodology was found to be severely harsh on improper installation due to poor design and/or defects, which resulted in roof life predictions that are less than 10 years. The most common installation/design error was roof flashing that did not meet minimum height requirements. In humid environments, mold growth on the PVC membrane was a common problem.

Roof Integrity – ASTM D 4434

Lab testing following American Society for Testing and Materials (ASTM) D 4434, *Standard Specification for Poly(Vinyl Chloride) Sheet Roofing*, was also used to evaluate roof integrity. The test results provide the quantitative metric that was used to compare different sections of the field-weathered PVC roof material to each other and the PVC specification standards.

The primary concern was premature degradation of the PVC roof membrane directly underneath the BIPV panel due to the greater temperature conditions the PV panels create. The results of the ASTM testing were inconclusive since the PVC membrane directly under the BIPV panel did not consistently yield significantly worse test results when compared to the PVC membrane that was away from the BIPV panel.

Renewable Energy Generation

The renewable energy generation performance objective utilized solar resource data collected by local weather stations and the power output data from the PV inverter or other energy- metering devices at Sites II and III. Site I already had existing monitoring equipment that collected similar data needed for this quantitative metric. The annual output and solar resource data helped determine the overall system efficiency. If the annual output corresponds to the estimated output, then the system met its renewable energy generation performance objective.

The PV systems generally met the expected energy output when looking at the mean conversion efficiency. Soiling due to environmental conditions was the primary factor impacting output. Soiling is most prominent on larger roofs that utilize interior drains due to the increased complexity in maintaining the slope for proper drainage.

Increased Energy Efficiency – Roof Reflectivity

The BIPV roofing system can potentially improve the energy efficiency of the building by reducing the load on the air conditioning system. The outer layer of the roof consists of a reflective PVC layer and a non-reflective PV layer. When compared to a conventional, dark roof, the cooling load on the building should be reduced. If the measured composite reflectivity of the PVC and PV materials does not fall below the measured reflectivity of the pre-existing roof, which is the baseline condition, then the system met this performance objective. This quantitative metric was originally planned to be studied at Site III only, but additional data was collected at the other sites during ROOFER EMS surveys. Reflectivity/albedo was determined using a modified version of ASTM E 1918 that Department of Energy Lawrence Berkeley National Lab (DOE LBNL) developed for smaller roof samples that LBNL calls E 1918A. This modified method was decided to be more accurate for measuring the PVC and PV components separately. The data collected can also be used to calculate albedo values according to ASTM E 1918, but is only provided in the appendices and was not used for assessing the BIPV roof.

The performance objective was met since the composite roof reflectivity values of the BIPV roofs during the demonstration period were generally greater than conventional dark roofs, but the degradation in the first few years was significant. This was primarily due to soiling and not actual roof membrane degradation. Since roof cleaning is not a typical DoD operations or maintenance activity, roof reflectivity was measured with the soiling during the site visits.

Increased Energy Efficiency – Reduced Air Conditioning Load at Site III

In addition, for Site III only, the energy usage of the air conditioning system was measured to characterize the performance of that system prior to installing the BIPV roof. Once the BIPV roof was installed, the air conditioning system and the weather will continue to be monitored during the demonstration period. Since the weather was not exactly the same in both the baseline and post-installation periods, the air conditioning energy consumption was normalized for weather and a resulting model using the measured data was used to compare the energy usage during two periods. The performance objective was met if the BIPV roof results in a net reduction to the air conditioning system's energy consumption and the result was used as a quantitative metric.

The data yielded inconclusive results due to the poorly insulated attic space. The poor insulation nearly eliminated the heat transfer from the roof to the occupied space, which resulted in immeasurable changes to the air conditioning energy consumption. However, temperature sensors in the roof did indicate significant temperature decreases after the BIPV roof installation.

Operations and Maintenance

Utilization of a BIPV roof system was expected to result in minimal O&M costs. Roof assessments and any available O&M records for the BIPV roof were collected and compiled to assess the O&M requirements of the BIPV roof at all three sites. If the level of effort required in operating and maintaining the BIPV roof does not exceed that of local conventional roofs, then the BIPV system met this qualitative performance objective.

The BIPV roof did not meet this performance objective at two out of three sites due to the maintenance required to maintain the PV system. The roofing membrane was generally maintenance free during the study period, but issues with damage to the PV panels and adhesion problems resulted in an increased maintenance requirement.

4.0 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

59 candidate buildings were submitted by the Air Force, Army, Marine Corps, and Navy for consideration. Site I was chosen because of the existing BIPV roof. Sites II and III were chosen based on the size of the roof, type of roof, age of roof, local resources to support the project, solar insolation, access to the facility, roof condition, and geographic location. A variety of seasonal weather conditions was desired for Site II. As for Site III, one of the objectives was to study the effects on the heating, ventilation, and air conditioning (HVAC) system, especially the benefits of a cool roof, so a site with very high solar insolation was desired. Also, the Site III pre-existing roof needed to be in good condition in order to establish an energy consumption baseline. Both sites were also chosen to be representative of geographically clustered DoD locations and to expose the BIPV roofs to a variety of weather conditions.

4.2 FACILITY/SITE CONDITIONS

Site I is a Base Exchange located at Luke Air Force Base (AFB) in Arizona (AZ). This site was chosen based on the ESTCP review board's recommendation, the large size of the BIPV roof, and the age. Site I (Luke AFB) has the same BIPV roof type that was installed at Sites II and III. Site II is a document storage facility at Naval Air Station (NAS) Patuxent River in Maryland (MD). Site III is an office building at Marine Corps Air Station (MCAS) Yuma in AZ.

Site I (Luke AFB) and Site III (MCAS Yuma) are in close proximity to each other and provided a good comparison of an older BIPV roof with a new one. Also, the BIPV roof at Site I (Luke AFB) was originally under an Energy Savings Performance Contract (ESPC), which had different O&M criteria from non-ESPC roofs and had its performance validated by a measurement and verification plan. This was to allow a comparison of O&M approaches, but the Luke AFB ESPC was terminated shortly after this ESTCP project started.

The roof at the Base Exchange at Site I (Luke AFB) is approximately 144,000 ft^2 and is equipped with a 122 kilowatt (kW) BIPV roof system installed in December 2005 (Figure-5). The BIPV roof was expanded to 375 kW in June 2006 to maximize the rebate received through the local utility. The PV laminates are estimated to cover about 42% of the roof.

Figure-5: Luke AFB BIPV roof being cleaned during adhesive-failure fix.

The Building 515 roof at Site II (NAS Patuxent River) is approximately 80 feet wide and 200 feet long and is a four-ply, flat, built-up, asphalt roof (Figure-6, left). The facility was built in 1942 and is a single story warehouse that has been converted to store contract documents. The roof has two small plumbing stack vents and the slope of the roof is 1/8 of an inch to one foot. The heights of the eaves range from 14 to 16 feet. The roof deck and support beams were rotten in up to ten locations. Due to the poor condition, the pre-existing roof material was removed, repairs were made, and the BIPV roof system was installed. The installed PV laminates cover about 27% of the roof, resulting in an installed capacity of 26.9 kW (Figure-6, right).

Figure-6: Before (left) and after (right) photos of Building 515 at NAS Patuxent River.

Building 228 at Site III (MCAS Yuma) is a 14-foot, single story, wood-frame building built in 1943 with a 9,270 ft^2 roof. The roof was in good physical condition and has one large exhaust vent with several small vents around the center (Figure-7, left). There was no indication that the thermal properties of the roof were compromised, so the BIPV roof system was installed on top of the existing roof. The pre-existing antennae cable was re-laid across the BIPV roof and held down by PVC strips so that the cable will not interfere with any of the solar panels or wear out the PVC membrane. The 20.6 kW of PV laminates cover about 36% of the roof (Figure-7, right).

Site III (MCAS Yuma) is cooled with two 30-ton Carrier water cooled direct expansion chillers and heated with a small 580,000 British Thermal Units (BTU) Parker water tube boiler. Two air handlers provide conditioned air to the space. The interior temperature is kept at 76-78^{o}F. For part of the building, the supply and return air duct systems are in the attic and one leak was visible. The floor of the attic is insulated with fiberglass pad insulation. However, some insulation appeared to be removed and some was deteriorated. The poor building envelope because of the attic naturally ventilated the roof with outside air. The ductwork and insulation remained unchanged for the baseline and post-installation demonstration periods. The interior ceiling height is 8-10 feet and the attic ranges 4-6 feet. The total wall area is 4730 ft^2 and the total window area is 478 ft^2. The building is operated 5 days a week from 6 am to 5 pm.

Figure-7: Before (left) and after (right) photos of Building 228 at Site III (MCAS Yuma).

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The objective was to demonstrate and validate whether BIPV roofs can result in an energy efficient roof and endure as long as conventional roofs. Site III (MCAS Yuma) had additional energy monitoring. Measurement of the heat flow through the Site III (MCAS Yuma) pre-existing roof help characterized the thermal elements. The post-installation period includes heat flow and energy characterization of both the single-ply PVC membrane and the BIPV panels.

Evaluation of the roof integrity at all three sites required periodic roof surveys using ROOFER EMS. This system includes procedures for collecting and maintaining roof condition data, surveying, rating, and evaluating roof conditions. The overall roof condition rating procedure uses standard inspection procedures and numerical indices for assessing the roof condition, which include separate condition indices for the membrane, flashing, and insulation. This data was entered into *MicroROOFER* software, which calculates an overall roof condition index (RCI). For the laboratory-testing portion, ASTM D 4434 for PVC roofs was used.

5.2 BASELINE CHARACTERIZATION

None of the sites had pre-existing rooftop PV, so renewable energy generation baselines were not applicable. The PVC reflectivity baseline was taken from the manufacturer specification data sheet and was determined by ASTM D-4434. The PV industry does not report reflectance values, so cleaned modules were used as the baseline. Roof condition indices of a new roof ideally scores 100, but ROOFER EMS results can be used to provide roof integrity reference points.

Data was collected to characterize the building's cooling energy use for the effects on the HVAC loads at Site III (MCAS Yuma). Both hourly and daily data was used and normalized with the outdoor weather data. The weekend data was used to more accurately characterize the effect of the building shell on air conditioning (A/C) energy use since the internal loads were limited to only some lighting during the weekend. The weekday data was used to integrate the effect of the building shell and the dynamics of the building's operation and internal loads.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The evaluations of the roofs at all three sites used standard procedures to establish numerical indices from data collected from visual inspections. Additional information was acquired from nondestructive moisture surveys and gravimetric analyses of core cuts.

The Site I (Luke AFB) energy monitoring system utilized the manufacturer's Renewable Energy Management (REM) system, which measured direct current (DC) power produced, alternating current (AC) power produced, AC energy produced, system voltage produced, PV panel temperature, below-surface temperature, ambient temperature, solar insolation, and wind speed. The plan was to use the ESPC annual verification reports to evaluate performance, but the ESPC was terminated shortly after this ESTCP project initiated. However, some raw data was acquired.

Similar equipment was used to evaluate the energy production of the PV system at Site II (NAS Patuxent River) and Site III (MCAS Yuma). A schematic of Site II (NAS Patuxent River) is shown in Figure-8. A thermocouple that measured the PV module temperature was located near the weather station. As indicated by Figure-8, the system is actually wired to accept an additional 7 kW in the event that the site decides to expand the system. Due to the condition of the PVC membrane, which is discussed later, there are currently no plans for the expansion.

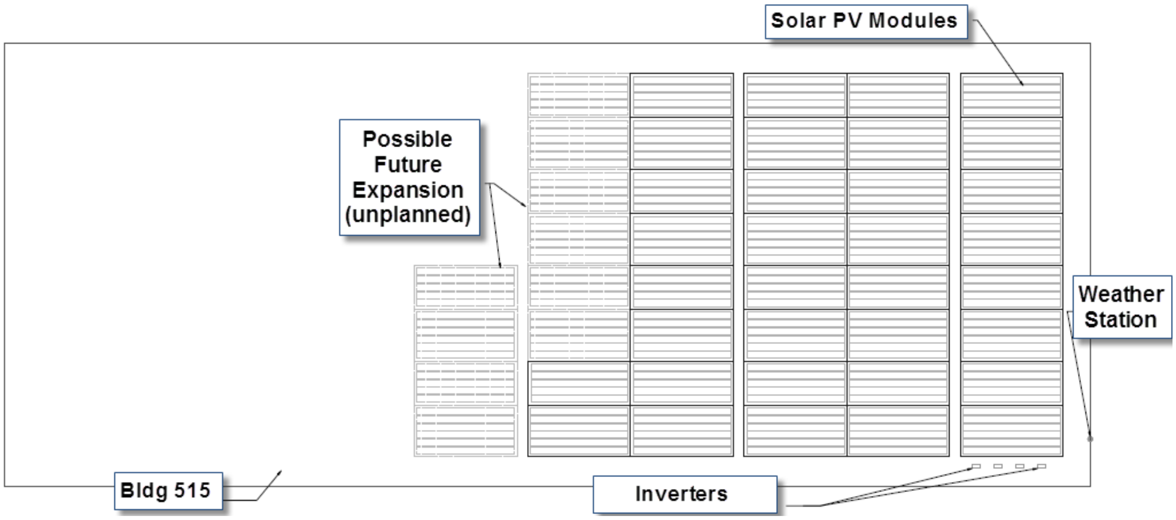

Figure-8: Diagram of major components on Building 515 at Site II (NAS Patuxent River).

A diagram of the Site III (MCAS Yuma) sensor locations are shown in Figure-9. In general, the parameters measured include the roof surface and underside temperatures, roof heat flux, indoor and plenum air temperatures, weather conditions, and whole-building energy use. In addition to the continuously monitored points, one-time measurements were made for, roof albedo/reflectivity before and after BIPV installation, wall and roof insulation levels, A/C nameplate and power, and internal equipment and power.

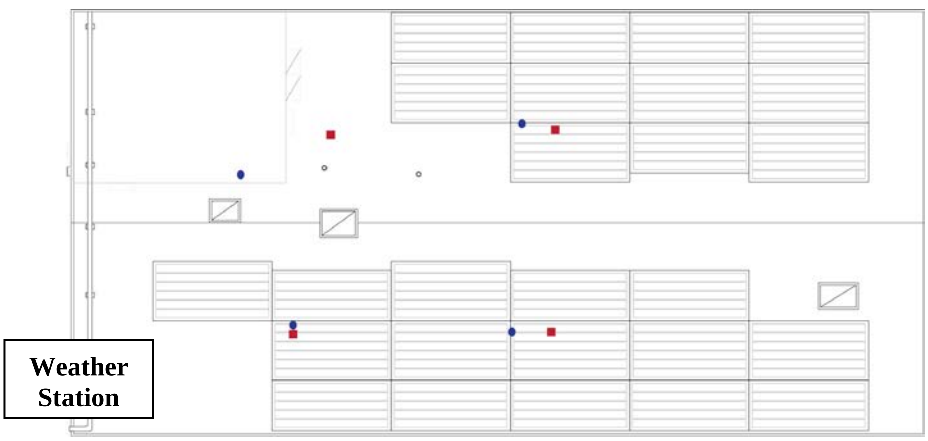

Figure-9: Temperature sensor locations at Site III (MCAS Yuma) during baseline and performance periods. Blue ovals indicate locations of roof deck underside sensors; red squares indicate locations of roof top surface sensors.

5.4 OPERATIONAL TESTING

The primary tasks performed during the planned testing period are shown in Figure-10. The timelines for the three demonstration sites were very similar once the BIPV roofs were installed. Except for the weather stations, no other equipment was installed for the evaluation of the roof integrity. Personnel who performed the surveys were trained in ROOFER EMS protocols, experienced with roof evaluation procedures and followed DoD safety requirements. ROOFER assessments were originally planned to occur annually in equal increments of time, but some schedules were shifted to align with significant project events or due to scheduling conflicts.

Task Name	Duration	Start	Finish
- Site I (Luke AFB) - 3 ROOFER Surveys	**826 days**	**Wed 8/13/08**	**Wed 10/12/11**
3 ROOFER Surveys	826 days	Wed 8/13/08	Wed 10/12/11
- Site II (NAS Patuxent River)	**720 days?**	**Tue 12/2/08**	**Mon 9/5/11**
BIPV Roof Construction	9 days	Tue 12/2/08	Fri 12/12/08
Data Collection & 3 ROOFER Surveys	660 days?	Fri 2/6/09	Thu 8/18/11
Site Report & Analysis	70 days	Tue 5/31/11	Mon 9/5/11
- Site III (MCAS Yuma)	**741 days?**	**Fri 5/1/09**	**Fri 3/2/12**
Energy Baseline	26 days?	Fri 5/1/09	Sat 6/6/09
BIPV Roof Construction	5 days	Mon 6/8/09	Fri 6/12/09
Post-Retrofit Data & 3 ROOFER Surveys	595 days?	Mon 6/15/09	Sun 9/25/11
Site Report & Analysis	115 days	Mon 9/26/11	Fri 3/2/12

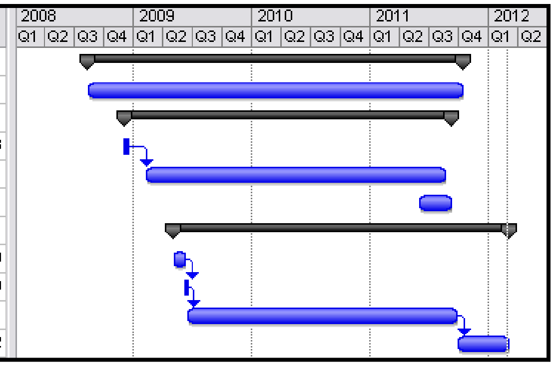

Figure-10: Approximate schedule of operational tasks for currently planned schedule.

Monitoring of the baseline cooling period of Site III (MCAS Yuma) commenced in May 2009, but data collection was initiated in early April 2009 to review data collection performance. After the baseline, the BIPV roof was installed. Installation of additional sensors and reinstallation of the weather tower and temperature sensors was coordinated with the contractor.

At the end of the ESTCP project, the temperature and heat flux sensors were abandoned in place since they do not interfere with the roof or operations of the building and they do not contain any residual value. The weather towers and data loggers are left to the local installation to use for monitoring beyond the ESTCP demonstration period.

5.5 SAMPLING PROTOCOL

The ROOFER EMS software roof evaluation tool can repeatedly provide objective roof condition scores to identify deterioration characteristics of the roof system. ROOFER EMS provides numeric scores ranging from 0-100. Each BIPV roof was surveyed a minimum of two times. An informal assessment was made at Site II (NAS Patuxent River) after hurricane Sandy, but nothing notable was found since the site was not severely affected by the storm.

For the energy-monitoring portion, both hourly and daily data was analyzed. The energy consumption-monitoring portion at Site III (MCAS Yuma) took into account weekend and weekday energy usage behavior. Periodic data reviews ensured that the monitoring equipment was performing properly. The following excerpt from the draft LBNL report describes the equipment used and data points that the equipment addresses for Site III (MCAS Yuma) [1]:

> Outside air temperature and relative humidity (RH) were measured using a Vaisala HMP45C-L probe, which was housed in a Campbell Scientific 10-plate naturally ventilated Gill radiation shield (model 41003-5). The shield was located about 70 cm above the roof on a weather tower mounted on the building near its southwest corner. Global horizontal solar radiation was measured using a Kipp & Zonen CMP3 second-class pyranometer. The device was attached to a Campbell Scientific leveling mount, which was in turn affixed to the south end of the weather tower cross-arm. The instrument was located higher than all nearby obstacles (including a nearby chimney) to avoid shadows. Wind speed was measured with a Gill Instruments WindSonic two-axis time-of-flight ultrasonic anemometer. The device was attached to the top of the weather tower, about 2 m above the roof. Measurements of precipitation at Yuma Marine Corps Air Station, AZ were obtained from Weather Underground.
>
> Three roof temperatures were measured in each roof quadrant (for a total of 12 roof temperature measurements) using Minco S667PD thin-film platinum resistance

temperature sensors connected to Minco Temptran TT176PD temperature transmitters. Before installation of the BIPV system four roof top surface temperature sensors were installed. Each of these temperature sensors was attached to the roof using construction adhesive and then covered with an approximately 150 mm-square piece of asphalt cap sheet patch. The patch was adhesively bonded to the existing roof cap sheet. Four temperatures were also measured on the wooden underside of the roof deck beneath the roof top surface temperature sensors. Each temperature sensor was bonded to the wood with epoxy. During the subsequent installation of the BIPV system, four additional temperature sensors were added. These sensors were located on the top surface of the BIPV system gypsum board in the middle of each quadrant. The temperature sensor in the northwest quadrant was underneath the exposed white membrane (without laminated PV) while the other three sensors were underneath the membrane with laminated PV.

Heat fluxes were measured at the underside of the roof deck near the middle of each roof quadrant using Hukseflux HFP01-L heat flux sensors. Each heat flux sensor was attached to the underside of the roof deck near roof underside temperature sensors using epoxy and oriented for positive heat flux downward through the sensor. During installation of the BIPV system, two additional Hukseflux HFP01-L heat flux sensors were installed in the roof. These heat flux sensors were located on the top surface of the BIPV system gypsum board in the northwest and southwest quadrants immediately adjacent to the surface temperature sensors. The heat flux sensor in the northwest quadrant was located underneath the exposed white membrane (without laminated PV) and that in the southwest quadrant was under membrane with laminated PV.

Four air temperatures in the attic, one air temperature in the ceiling return plenum (northwest quadrant), and three air temperatures in conditioned spaces were measured using Campbell Scientific 108-L probes. In the attic and return plenum, the probe tips were suspended near the mid-height of the associated space. In each conditioned space, the probe tip was suspended about 8 to 10 cm below the ceiling.

Power drawn by each of the five HVAC system components (i.e., both sets of compressors and air handling units, and the evaporative condenser) and the entire building (including HVAC system power) was measured using Continental Control Systems WattNode WNB-3D-240-P three-phase four-wire power meters. Each power meter was connected to three Continental Control Systems split-core current transformers. During installation of the BIPV system an additional power meter of the same type was installed at the connection of the PV inverters to the building main power to measure PV power production, P_{PV}.

Building plug load, P_{other}, was calculated as

$$P_{\text{other}} = P_{\text{building}} - P_{\text{HVAC}}, \tag{1}$$

where P_{building} is the total building load. (P_{building} was corrected for PV power production after installation of the BIPV system.) P_{HVAC} is the total HVAC power load, calculated as

$$P_{\text{HVAC}} = P_{\text{c1}} + P_{\text{c2}} + P_{\text{ahu1}} + P_{\text{ahu2}} + P_{\text{ec}}. \tag{2}$$

Subscripts c, ahu, and ec correspond to the compressor, air handler, and evaporative condenser, and subscripts 1 and 2 correspond to components for the south side (AHU1) and the north side of the building (AHU2).

Measurements were recorded by a pair of Campbell Scientific XP-CR1000 24-bit programmable data loggers. The instrumentation and data loggers were installed and

commissioned in early December 2008. Each sensor was scanned once a second and average values were recorded every 30 seconds.

The Site II (NAS Patuxent River) instrumentation was similar and is summarized below:

Measured Parameter	Manufacturer and Model
Ambient Temperature / Relative Humidity	Kele GEH5-O-TT2
Wind Speed	Kele A70-SL
Rain	Kele A70-RL
PV Surface Temperature	Omega RTD-830
Roof Surface Temperature	Omega RTD-830
Pyranometer	Apogee SP-215
Energy Meter	Veris H-8163-0200-1-3

5.5.1 Calibration of Equipment

ROOFER EMS does not require calibration. As for the energy monitoring equipment, the data acquisition system were set up and tested to ensure the system performed as expected prior to deployment and installation. New sensors were purchased pre-calibrated from the manufacturer.

5.5.2 Quality Assurance Sampling

ROOFER EMS does not require roofing experts to conduct the inspections and is designed to provide consistent results regardless of the inspector and has been proven effective throughout DoD. The data collected for the energy monitoring were downloaded and reviewed periodically to ensure that the monitoring equipment is performing within established parameters.

5.6 SAMPLING RESULTS

The ESPC at Site I (Luke AFB) was terminated soon after this ESTCP project was approved, so the ESPC annual verification reports were not available for use. Raw data was acquired directly from the manufacturer. Due to problems with the data collection system, only energy (Figure-11) and power data (Figure-12) for April 1, 2011 to May 12, 2011 appear valid. Note that Figure-13 shows the solar resource as sun hours in kWh/m^2/day. Also known as solar insolation or irradiance, this value is the equivalent number of hours the sun is producing 1000 W/m^2 in a day. This convention is convenient because the PV industry rates a PV module's power capacity under Standard Test Conditions (STC), which basically consists of 1000 W/m^2 of solar irradiance on a PV module at a temperature of 25^{o}C and a reference solar spectral irradiance called Air Mass 1.5, and allows the PV system planner/designer/evaluator to quickly estimate the expected energy production. Comparing the measured energy production to expected energy production based on the available solar resource will determine the effectiveness of the PV system in providing renewable energy.

Site I (Luke AFB) ROOFER EMS condition indices are shown in Table-2. The RCI, Membrane Condition Index (MCI) and Flashing Condition Index (FCI) provide an overall assessment of the roof over time. However, note that ROOFER is currently designed to only assess conventional roofs and not BIPV roofs, so issues with the PV modules may be difficult, if not currently impossible, to account in ROOFER and, thus, may not impact the condition indices. However, the indices still provide an indication of how well the PVC portion of the roof endures over time.

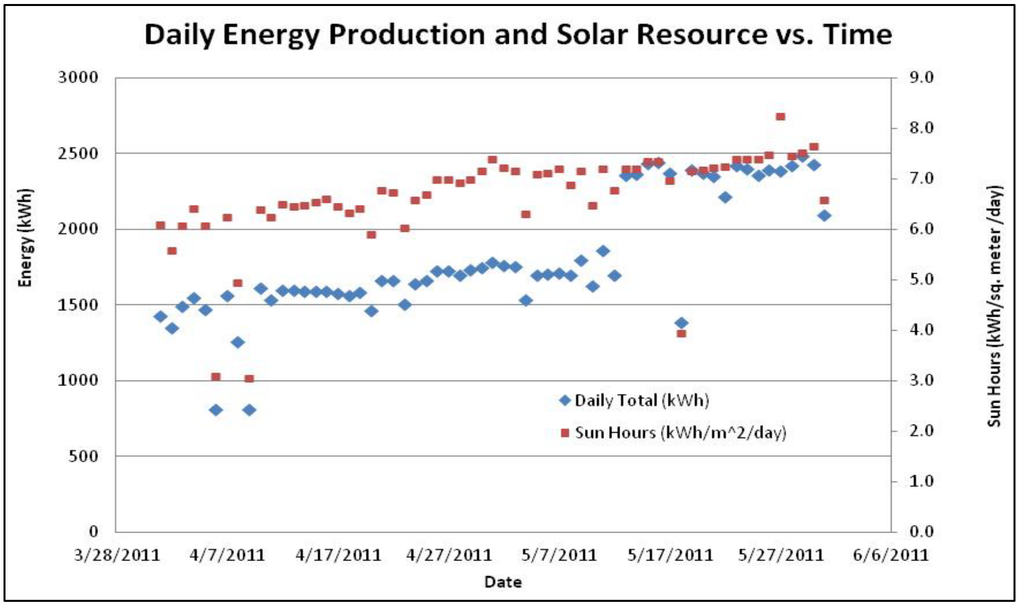

Figure-11: Total daily energy production and solar resource from April to May 2011 at Site I (Luke AFB).

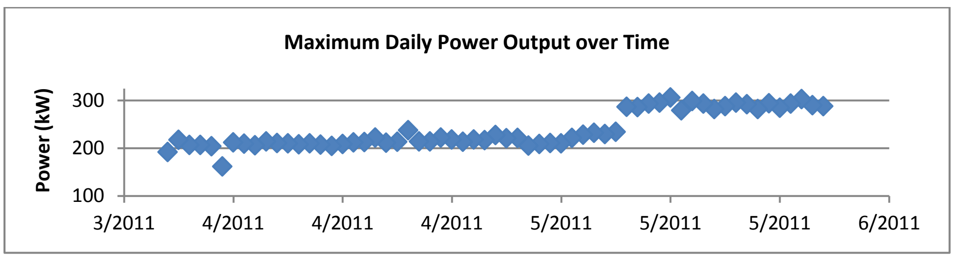

Figure-12: Maximum daily power output for April-May 2011 at Site I (Luke AFB)

Table-2: Site I ROOFER EMS survey and analysis results.

Date	RCI	MCI	FCI
AUG 2008	94	96	94
MAR 2010	94	95	94
OCT 2011	94	94	94

The left photo in Figure-13 shows the bond failure between the PV and PVC carrier sheet. Since the PVC carrier sheet may still provide for a water tight roof assembly, problems experienced by the PV modules may not impact ROOFER scoring. In response to the bond failure, the PV manufacturer taped the frame around the PV to the adjacent PVC membrane in an attempt repair the problem in May 2010 (Figure-15, right). Unfortunately, some of the tape deteriorated less than six months after it was applied. The deteriorated tape exposed adhesive residue, which collected dirt and reduced the overall reflectivity. Figure-14 shows some of the tape deterioration along with soiling of the PV modules. The significant soiling was a result of the low-slope

surface, which does not allow for all the water to completely leave the area and causes any dirt trapped by the water to settle on the roof after the water evaporates. The soiling on the PV modules will reduce the overall roof reflectivity and the energy output of the PV system.

Figure-13: Bonding failure (left) and tape solution (right) between PVL and PVC at Site I (Luke AFB).

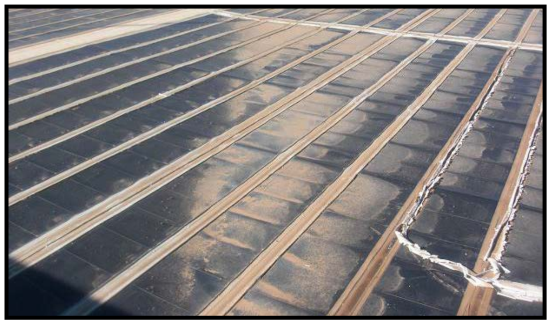

Figure-14: Tape detoriation and soiling of the PV system at Site I (Luke AFB).

Measuring BIPV reflectivity at Site I (Luke AFB) was not originally part of the scope, but since soiling was significant, the ROOFER survey team collected the data while on site. Table-3 shows the calculated roof and PV reflectance values (i.e., albedo), based on the average of the measured results. Note that the only time the PV was cleaned was when the roof was being prepared for the tape solution. The other measurements are for naturally soiled surfaces.

Table-3: Site I average PVC membrane and PVL reflectance values.

PVC Albedo	PVL Albedo
PVC Specification 0.83 = reference	MAY 2010 PV, cleaned 0.24 = reference
MAY 2010 PVC, soiled 0.76 = 8% reduction	MAY 2010 PV, soiled 0.23 = 4% reduction
OCT 2011 PVC, soiled 0.59 = 29% reduction	OCT 2011 PV, soiled 0.18 = 25% reduction

Site II (NAS Patuxent River) experienced problems with sensors and remote communication soon after the BIPV roof installation. The following is from the contractor's report.

> There were gaps in the data due to telephone line connection and sensor failures. At times, the phone line would not connect to the data logger and some data was lost. After several attempts to correct the problems with the phone line, local site personnel collected data directly from the data logger and forwarded the data to the analysts. In particular, data from June and July 2009, February 2010, and August 2010 were lost. Missing data appears as gaps in the data seen in the forthcoming charts.

The original outside air temperature and humidity sensor was a GE model. After it failed, it was replaced with a Veris model. It is believed that these failed because high humidity associated with the site being located so close to Patuxent River. The roof and PV surface temperature sensors and transmitters were replaced after they began to produce temperature reading well above and below the expected ranges. These surface temperature sensors may have failed due to the hot roof environment. Data from the Patuxent River weather station (KNHK) located 1.2 mile east of building 515 were used for reference in determining if sensors were operating within expected range. The PV power meter stopped working. To correct this, the voltage leads were reconnected.

Figure-15 shows the power output of the PV system over the course of the monitoring period, which was from February 2009 to February 2011. Figure-16 shows the energy output of the PV system as it relates to the measured global, horizontal insolation at the Site II (Patuxent River).

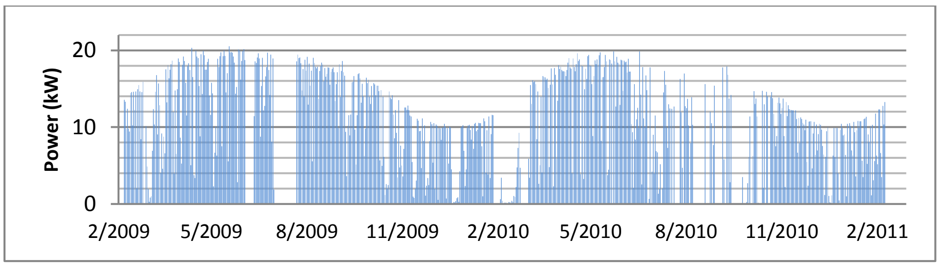

Figure-15: Power output over time at Site II (NAS Patuxent River).

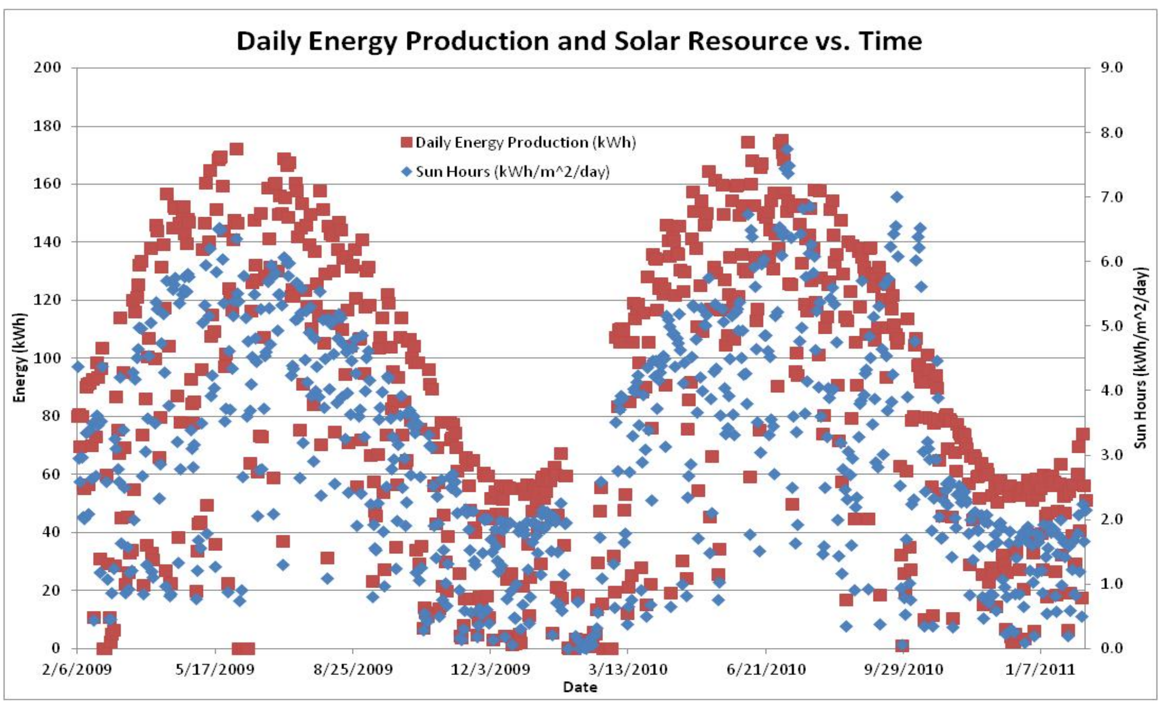

Figure-16: Total daily energy production and solar resource over time for at Site II (NAS Patuxent River).

Wind speed, its impact on the PV surface temperature, rain, its ability to reduce or increase soiling, and the reduction in solar insolation due to cloud cover were compared against the power

output. The most significant correlation to PV power output is the solar resource and the other weather-related factors do not identify any significant trends.

Site II (NAS Patuxent River) ROOFER indices are shown in Table-4 and albedo values in Table-5. The indices were significantly impacted by mold growth on the PVC, a warping deck, and water ponding. Only one quality PVC albedo value was acquired due to a lack of clear skies. It was impossible to properly measure the PV albedo due to water ponding (Figure-17).

Table-4: Site II ROOFER EMS survey and analysis results.

Date	RCI	MCI	FCI
JUL 2009	91	90	90
OCT 2010	85	81	88
JUL 2011	80	74	88

Table-5: Site II average PVC membrane reflectance.

PVC Albedo	Vs. Spec
0.83 – Original PVC Specification	
0.63 – JUL 2011 PVC, soiled	- 24 %

Figure-17: Site II (NAS Patuxent River) water ponding.

Soon into the Site III (MCAS Yuma) baseline period, the fan starter needed repair and the HVAC system needed to be recharged with refrigerant. The unexpected problems complicated the energy efficiency assessment since the pre and post-installation conditions were not entirely consistent. However, thermal measurements were unaffected and show that the BIPV roof did have a significant impact (Figure-18). Weekend data was excluded to be consistent for the air conditioning portion of the study. Detailed graphs are available in the DOE LBNL report [1].

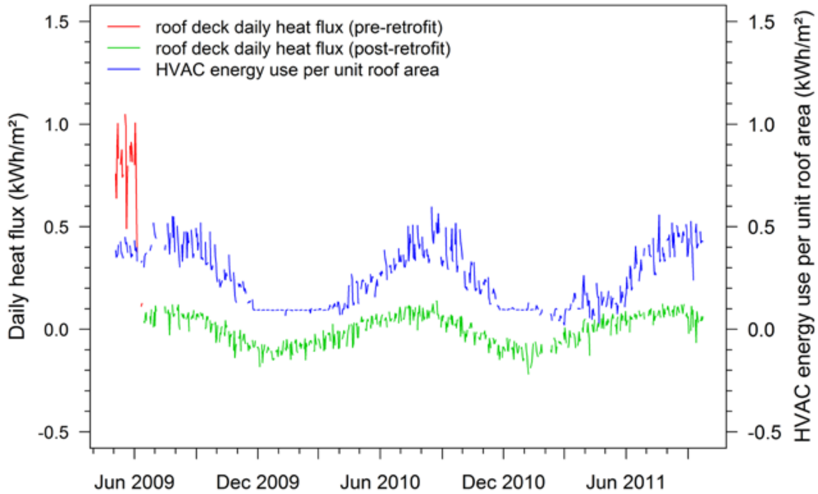

Figure-18: Site III daily, weekday heat flux through roof deck in the pre and post-BIPV roof phases and A/C energy use.

Site III (MCAS Yuma) PV energy production was low during the winter, but conversion efficiency was relatively constant over time (Figure-19).

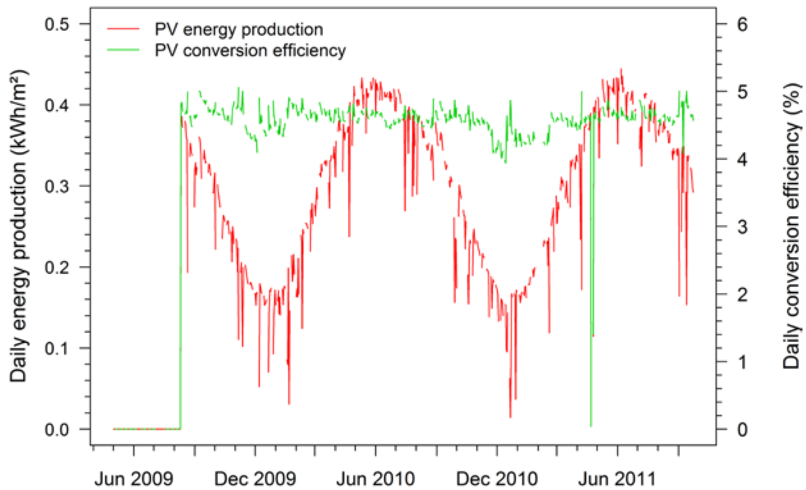

Figure-19: Site III daily PV energy production per unit PV surface area and mean PV conversion efficiency over time.

Site III (MCAS Yuma) ROOFER "w/ patch" indices are a result of the PVC samples taken for the tests discussed later (Table-6). ROOFER treats the patch as repair work. For fairness, indices without the patch were generated. The lowered FCI value was due to flashing height not meeting the six-inch requirement, which is needed to reduce the risk of water penetration. Reflectance results are shown in Table-7. October 2011 values were not attained due to the unexpected removal of the ladder needed to safely transport the instrument. However, visual inspections indicated that the soiling had decreased by Oct. 2011. This determination is further supported by the PV conversion efficiency analysis that is presented in the next section. Despite the soiling, the Site III (MCAS Yuma) BIPV roof appeared to have aged well (Figure-20).

PVC samples were taken from Site III (MCAS Yuma) underneath the PV modules and from an open area near the PV modules for ASTM D-4434 tests that addresses conditioning, overall thickness, tensile strength at break, breaking strength, elongation at break, seam strength, heat aging, tear resistance, tearing strength, low temperature bend test, and accelerated weathering. These samples were first field weathered from June 2009 to October 2010, which exposed them to two Arizona summers. Tests with marginal or poor results or are shown below in Table-8.

Table-6: ROOFER results from surveys at Site III (MCAS Yuma).

Date	RCI	MCI	FCI
DEC 2010	95	98	94
OCT 2011 w/o patch	95	98	94
OCT 2011 w/ patch	89	85	94

Table-7: Site III average PVC membrane and PVL reflectance values.

PVC Albedo	PVL Albedo
Original Gray Cap-sheet 0.25 = measured comparison	N/A
PVC Specification 0.83 = reference	MAY 2010 – cleaned PV 0.24 = measured reference
MAY 2010 PVC, soiled 0.77 = 7% reduction	MAY 2010 – soiled PV 0.17 = 29% reduction

Figure-20: Photo of Site III (MCAS Yuma) in October 2011, 16 months after installation.

Table-8: Notable results from select ASTM D-4434 tests used to evaluate PVC membranes. MD stands for tests in the machine direction and XMD stands for tests in the cross machine direction.

Test	Requirement	PVC under PV	PVC in Open Area
Overall Thickness per ASTM D751	min. 1.14 mm (0.045 in.)	.046 in	.0483 in
Overall Thickness per ASTM D751 MD	min. 1.14 mm (0.045 in.)	.0463 in	.0479 in
Post Heat Aged Elongation per ASTM D751 , A - Grab Method -XMD	min. 90% of original	92%	90%
Seam Strength per ASTM D751, A - Grab Method	min. break strength (150 lbf/in)	180.2 lbf/in	156.5 lbf/in
Tearing Strength per ASTM D751 , B -Tongue Tear Method (8x8) -MD	min. 200 N (45.0 lbf)	37 lbf	35 lbf
Tearing Strength per ASTM D751, B -Tongue Tear Method (8x8) -XMD	min . 200 N (45.0 lbf)	52 lbf	54 lbf

Qualitative inspections of other BIPV roofs similar to those in this study were made. This type of BIPV roof endured well in some areas and some of the notable deficiencies were due to poor construction and practices. In one location, the tape solution prevented water drainage. That same system also experienced significant mold growth due to its tropical environment. Another system experienced localized mold growth due to water ponding (Figure-21, left). The right photo in Figure-21 shows discoloration indicating that the encapsulation of the PV laminate has been compromised. This occurred only in areas where there was significant water ponding, but it is possible that the damage was actually due to snow build-up and the exposure of the encapsulation to freezing temperatures. Interestingly, the tape solution appeared to be unaffected.

Figure-21: Severe, localized mold growth due to water ponding (left) and PV delamination (right).

6.0 PERFORMANCE ASSESSMENT

6.1 ROOF INTEGRITY – ROOFER EMS

ROOFER EMS software takes the condition indices it generates and compares them to its built-in predictive life curves to estimate roof longevity. The data presented in Section 5 shows that none of the three BIPV roofs achieved condition indices of 100 even soon after commissioning due to how ROOFER treats non-ideal roof characteristics as defects. For example, a roof vent with insufficient flashing height was deemed a defect. However, the rate of roof degradation is what determines its life. Site I (Luke AFB) and Site III (MCAS Yuma) both showed very little-to-no change to their indices, whereas Site II (NAS Patuxent River) showed a significant reduction in its MCI due to mold growth on the PVC membrane. While Site I (Luke AFB) experienced significant soiling due to dirt build-up and failure of the PV adhesive, those factors at the time did not impact the roof integrity, which is why the condition indices were consistently high. In general, the performance objective was not met, but the issues resulting from design mistakes, such as the insufficient flashing height, could be remedied in future systems.

6.2 ROOF INTEGRITY – ACCELERATED WEATHER TESTING

Since ROOFER EMS requires a longer period of time in order to better predict roof life, an independent laboratory tested the field-weathered PVC samples. The results of the tests were not significantly different for the two set of samples so it is inconclusive in whether the different environmental conditions significantly shorten the life of the PVC membrane. It is also possible that the higher temperature conditions on one PVC sample had the same effect as the higher solar exposure had on the other. Longer field weathering may also provide different test results, but the project length and amount of time needed for longer accelerated weathering tests made it difficult for this study. More tests are needed to make definitive conclusions.

6.3 RENEWABLE ENERGY GENERATION

The following table summarizes the real world, renewable energy output performance and allows for a simple way to compare the three BIPV systems. Since the systems are of different sizes, age, and locations, the simplest way to compare one system's renewable energy generation performance against another system's is to look at the average energy output per unit area. The longer the time-scale the average is based off of, the more accurate the value is in representing the systems effectiveness.

Table-9: Renewable energy performance of the three BIPV sites.

Location	Data Period	System Rating (kW)	Peak Instantaneous Output (kW)	Average Energy Output (kWh/day)	Average Energy Output (kWh/day/m^2)
Site I (Luke AFB)	4/2011 – 5/2011	375	309	1,812	0.32
Site II (NAS Patuxent River)	2/2009 – 2/2011	26.9	23.1	81.9	0.20
Site III (MCAS Yuma)	8/2009 – 9/2011	20.6	29.7	92.7	0.28

Site I (Luke AFB) data shows that the maximum daily output was often between 200 kW and 300 kW (Figure-12). While the installed capacity is rated at 375 kW, recall that the system should only be expected to produce power at that level under STC. To properly assess performance, the output was compared to the available solar insolation and the PV system was determined to be producing only about 80% of what it was expected to. Starting on May 13th,

when the energy production significantly increased, the PV system performed as expected. This was likely due to natural soiling of the PV modules. However, without detailed weather data, it was impossible to correlate actual weather events. While Site I (Luke AFB)'s data was limited, the performance objective was met since the PV system was able perform to expectations.

The two years of data for Site II (NAS Patuxent River) was more extensive. As expected, the output was lower in the winter. Furthermore, the site mainly experienced partly to mostly cloudy weather. However, when comparing the energy output against the available solar insolation, the BIPV system performed above expectations, thus, exceeding the performance objective (Figure-22). This can be accredited to the fact that thin film PV material tends to perform relatively well in diffuse sunlight when compared to crystalline PV material and this data provides evidence that the characteristic should be considered when developing future PV systems in similar climates. Note that at times when the performance appeared exceptionally high, such as over 150% of the expectation, this often occurred when the solar insolation was very low, such as early or late in the day or during heavy rainfall, so it has a very minor impact on the overall energy production.

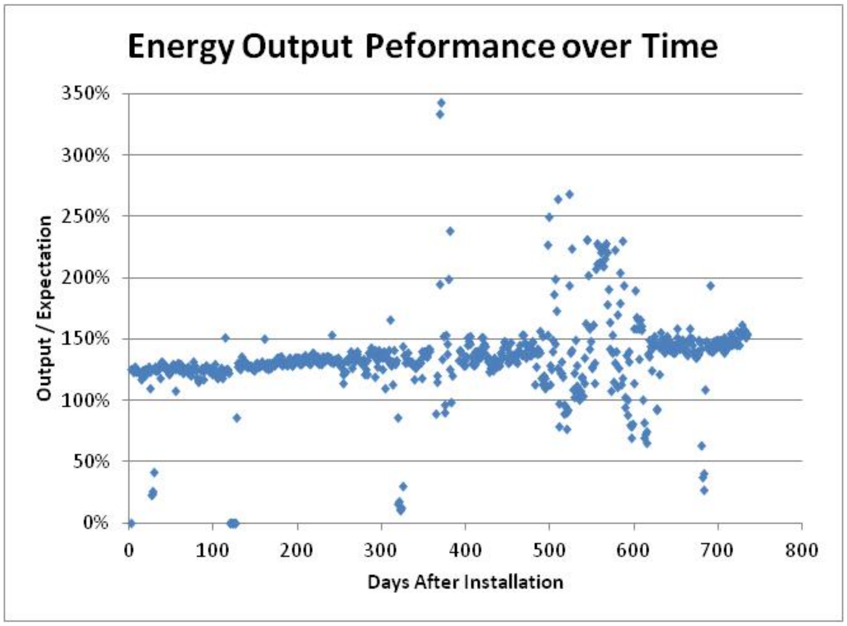

Figure-22: Site II (NAS Patuxent River) performance compared to estimates based on available solar resource.

Site II (NAS Patuxent River) PV performance was assessed against other collected weather data. Wind speed did not have a definite impact to PV module temperature and did not show any correlation to solar irradiance. Regardless of the irradiance, power output performance was initially seen to increase with PV module temperature, but this was likely due to more direct sunlight coinciding with a warmer environment. Note that PV manufacturer data sheet shows that the power output decreases linearly at a rate of -0.21% per degree Celsius above 25^{o}C at STC. However, the data is too spread out under real world conditions to verify that effect.

The amount of precipitation had a definite impact to the power output as the weather would be cloudy and water hinders the transmission of sunlight to the PV modules. As expected, the Site II (NAS Patuxent River) PV system produced more power when the rainfall was lowest. However, rain often helps remove soiling from a PV system. Unfortunately, the data did not show any

noticeable change in power output before and after a rain event and is likely due to residual water. There was a lack of snow events, so snow impacts could not be quantitatively determined, but it is expected that snow retention on the roof will significantly reduce the PV power output more than the water retention and possibly damage the PV modules (Figure-21, right).

Instrumentation at Site III (MCAS Yuma) was the most extensive due to the additional instrumentation for the A/C study. Data shows that the solar irradiance and mean wind speed are slightly synchronized with higher summer values. Figure-19 shows the energy output was lower in the winter, but the PV efficiency was relatively constant throughout the year. Visual inspections of the Site III (MCAS Yuma) BIPV roof showed that desert soiling is a recurring problem, so it was likely that winter rain helped clean the PV system to maintain its efficiency. Weekly data shows that the efficiency does increase temporarily after major rain events, but the size of the benefit varied and was possibly due to the amount of the prior soiling. Analyzing the energy generation and PV efficiency against outside air temperature under a smaller time-scale shows that both are fairly constant, which mean that this type of PV module performs fairly well in hot, desert conditions. For a typical summer day, the data shows that power output increases steadily over time before peaking around noon then decreases almost symmetrically while the PV efficiency was more level throughout the day and had a slight local minimum point around noon. As with most objects exposed to the sun, the PV module is typically at a higher temperature shortly after solar noon, which could explain the drop in efficiency. The data showing that the PV system reached its expected operational efficiency as early as 0700 and maintaining it as late as 1700 confirms the manufacturer's claim that this a-Si PV module works well with diffused sunlight. Occasional power output exceeding the system rating only indicates conditions better than STC. In summary, Site III (MCAS Yuma) met the performance objective.

6.4 INCREASED ENERGY EFFICIENCY – ROOF REFLECTIVITY

Roof albedo was originally planned to be measured for only Site III (MCAS Yuma), but since there were different soiling/aging/degradation conditions at all three sites, measurements were made for comparison. Albedo data for Site I (Luke AFB) in Table-3 shows that the PVC membrane became significantly less reflective during the course of the study. Visual observations confirmed that this was due to natural soiling by desert dust and dirt. The PV modules also experienced the similar soiling effects. While the albedo value in 2011 is much lower than in 2010, it is not expected that this rate of albedo decrease is constant due to precipitation events. The impact of precipitation events on PV efficiency was evident for Site III (MCAS Yuma) and this was directly tied to how soiled the PV modules are. As can be seen in Figure-14, the dirt build-up is uneven and visual observations of the soiling pattern indicate that precipitation and how it drains off the roof have definite impacts on which parts of the BIPV roof is soiled and which parts are not. Based on the complex layout of the roof, it does not appear that precipitation will ever completely remove the soiling. This short term data indicates that the BIPV roof albedo will likely be roughly 5-30% lower than what it was when it was assembled.

As of July 2011, which is about 31 months after the BIPV roof installation at Site II (NAS Patuxent River), the albedo of the PVC membrane was measured to be 24% less than what the manufacturer reported in the product specification. Since Site II (NAS Patuxent River) experiences frequent precipitation events, the reduction is much more due to mold growth on the PVC instead of soiling due to dust and dirt. Unfortunately, since mold is not easily removed without being likely to damage to the roof, the albedo value is expected to get progressively lower over time. Based on the one data point, the PVC albedo value was reduced by about 9%

per year. However, the exposed PVC membrane is the only part of the roof that is experiencing the wet environment, so the portion covered by the PV modules should be unaffected. Also, as mentioned earlier, it was not possible to accurately measure the reflectance of the PV modules due to the water ponding at the time of the measurement.

The original aged, built-up roof at Site III (MCAS Yuma) was measured to have an albedo of 0.25. For comparison, the spatial average of the new BIPV roof is 0.59. In about a year after installation, the PVC portion lost 7% of its reflectivity and the PV modules lost 29% of their reflectivity (Tables-7 and -8). The reflectivity of the PV modules appear to have significantly degraded, but when looking at the reflectively values, the PV reflectivity was reduced by only 0.07 whereas the PVC membrane reflectivity was reduced by 0.06 from their conditions as new. Note that the Site III (MCAS Yuma) roof is relatively simple compared to the Site I (Luke AFB) roof in that it is small and had a constant slope from a single ridge line, which allowed the PVC at Site III (MCAS Yuma) to remain relatively clean. The change in albedo values reduces the spatial average to 0.53, which is about a 10% reduction in the overall albedo value.

For comparison, one past study performed by DOE Oak Ridge National Laboratory at their site in Tennessee, shows that the white thermoplastic-olefin (TPO) membrane roof they tested started with a reflectance value of 70.5 and experienced a 12.3% reduction in reflectivity in its first year then fluctuated around a 14% reduction for the following two years[2]. The mean annual reduction in reflectance value was 5.7%. Their report did not indicate any issues with mold growth. In comparison to that DOE study in regards to roof reflectance, Site I (Luke AFB) performs worse due to dirt/dust build-up at certain times of the year, Site II (NAS Patuxent River) performed worse due to the mold growth, and Site III (MCAS Yuma) performed the same. Regarding the criteria established for this performance objective, the three BIPV roofs were determined to have met the performance requirement since the overall reflectivity of the BIPV roofs were still high even after the degradation.

6.5 INCREASED ENERGY EFFICIENCY – A/C LOADS

As originally planned, the building envelope and thermal impacts were studied at Site III (MCAS Yuma) because of the concern about potential heat gain due to the PV modules and actual benefit of the cool roof portion due to the PVC membrane. For a desert climate, the greatest thermal impact is normally in the summer when the temperature is highest. Therefore, in order to maximize the performance monitoring period, only the energy baseline during the cooling season was determined for the facility. Daily building energy use data shows that the energy consumption during the summer was 2.5 times that of the winter.

BIPV roof impact on temperature was not clear by just looking at the graphs. However, Figures-18 shows a significant heat flux change after the BIPV roof was installed. For comparison, standard heat transfer equations using spatial average roof temperatures at different locations of the roof assembly, the estimated thermal resistance of the original roof is 0.20 m^2-K/W whereas it is 0.47 m^2-K/W for the BIPV roof. Note that since the Site III (MCAS Yuma) BIPV roof was installed on top of the original roof, the thermal resistance for the final roof assembly is actually a sum of the two and is estimated to be 0.67 m^2-K/W. Actual heat transfer dynamics is much more complicated than just comparing the thermal resistance values, but the data shows that a significant reductions in the heat flux through the roof surface and deck occurred as expected. The actual thermal resistance of the ceiling and heat flux through the ceiling are unknown and

the poor condition of the attic, as described earlier, would not have resulted in the heat flux through the ceiling to be closely correlated to the heat transfer from the roof.

The assessment of the impact to the A/C system was more complex, the change is not evident from the data, and was complicated by repairs made to the A/C equipment soon after the BIPV roof installation. The majority of the A/C energy consumption during the cooling season was due to the compressors. They were not used during the winter season, which resulted in air handling units (AHU) making up the majority of the A/C energy consumption during that time. Heating was provided by a natural-gas fueled boiler and, thus, did not contribute to the electricity use.

Early July 2009 data showed decreases in daily energy consumption for AHU2 and increases for compressor 2, but these changes were more likely due to A/C repairs performed three weeks after the BIPV roof installation. Attempts were made to quantify the effect of the repair on the A/C energy consumption by correlating energy use before and after the repair and by using energy use data from the non-repaired equipment as an energy use basis for the repaired equipment, but it still was not possible to appropriately quantify the change due to the BIPV roof because the energy use of AHU1 and AHU2 appear to be independent based on the available data. To further complicate the situation, the heat flux through the ceiling was only minimally affected by the BIPV roof, which suggests that the observed decreases in A/C energy use were mostly attributed to the A/C repairs. This means that the assessment of the A/C impact was inconclusive when solely using the energy consumption data.

To continue with the A/C assessment, DOE-2.1E was used to simulate building energy usage of a 455 m^2 prototypical office building and estimate the electricity savings for the cooling season and the natural gas savings for the heating season. Long term Yuma weather data was unavailable, so Phoenix was chosen. The results showed an annual cooling energy savings of 9.6 kWh/m^2 (34.6 MJ/m^2), annual heating energy savings of 2.9 MJ/m^2 (0.010 $therm/m^2$) and a source energy savings of 107.1 MJ/m^2 (101 $kBTU/m^2$). Source energy savings refers to the fuel energy saved. For example, if it takes 3 kWh of energy content of coal to produce 1 kWh of useful electrical energy at the point of use (e.g., at the compressor), the source energy is the 3 kWh of coal. Similar estimates were made using DOE-2.1E for other locations to assess DoD-wide applicability of BIPV roofs and the results are shown in the following table.

Table-10: Simulated HVAC impact at various locations throughout the U.S. ΔC (kWh/m^2) is the annual cooling savings; ΔH (MJ/m^2) is the annual heating energy savings; ΔS (MJ/m^2) is the annual net source (a.k.a. primary) energy savings a prototypical office building after installation of the BIPV system.

San Diego, CA			Seattle, WA			Norfolk, VA			Jacksonville, FL		
ΔC	ΔH	ΔS	ΔC	ΔH	ΔS	ΔC	ΔH	ΔS	ΔC	ΔH	ΔS
6.2	2.2	68.8	3.7	17.8	57.8	5.3	13.3	71.1	7.3	5.1	83.5

6.6 OPERATIONS AND MAINTENANCE

Site I (Luke AFB) was the only site out of the three where maintenance and repair was performed. The PV bonding failure resulted in the May 2010 tape fix shown in Figure-14. While the bonding failure did not occur throughout the PV system, the PVL manufacturer applied the tape solution on the entire PV system as a preventive measure. However, as can be seen in the photograph, some of the tape deteriorated later that year, so the tape needed to be reapplied. In

addition, Site I (Luke AFB) required the replacement of one BIPV panel (i.e., an entire set of PVLs bonded to one carrier PVC sheet) because at least two of the PVLs were corroding due to water penetrating the encapsulation.

Site II (NAS Patuxent River) did require some maintenance due to a pin-size hole in the PV, but there was difficulty in finding local personnel to perform the maintenance due to the need to operate a small flame to patch the hole (Figure-23). Corrosion is expected to spread to the rest of the cell. Fortunately, the PVL includes bypass diodes connected across each cell, which allows the rest of the cells in the PVL to continue to produce power. The mold growth that was shown earlier is also a concern, but as it was stated earlier, an attempt to remove the mold will likely cause more damage to the roof. The only way to stop additional mold growth is to keep the roof dry, which is impractical, so the only remaining practical course of action is to ensure that the roof remains water tight, such as by surveying the roof every one-to-two years, and replacing the roof at its end of life. The tape solution was not applied to this site due to the lack of the PV bonding problem and the desire to study the BIPV roof as it was originally designed.

Figure-23: Corrosion of PV material due to a pin-size hole at Site II (NAS Patuxent River).

Out of the nine roofs that were visited during this study, the Site III (MCAS Yuma) BIPV roof was the one in the most pristine condition. However, it is also one of the newest of the nine. The last time the BIPV roof was surveyed was about 2.5 years after the installation. The PV bonding problem at Site I (Luke AFB) was not noticed until about 4 years after the installation. The tape solution was not applied to Site III (MCAS Yuma) due to the lack of the PV bonding problem and the desire to study the BIPV roof as it was originally designed.

Other sites that were visited included BIPV roofs at General Services Administration Waltham, Marine Corps Base Hawaii Kaneohe Bay (two BIPV roofs at this location), Camp Shields in Okinawa, Naval Base Guam, and NAS North Island. Only the BIPV system at Camp Shields was reported to have experienced the PV bonding problem, but all of the above sites received the tape fix as a pre-emptive measure. Sandia National Laboratory's BIPV roof was not visited, but the site point-of-contact confirmed that they did not experience any PV bonding problems. Unfortunately, at one of the visited sites, the tape caused additional water ponding and soiling due to the orientation of the tape being perpendicular to the direction of water drainage. One site did experience a problem with an inverter, but it failed within warranty and was scheduled for replacement.

Several non-government BIPV system owners were contacted to request information on the O&M for their systems, but there was difficulty in finding knowledgeable facility personnel to interview. The few that claimed that their system was working fine were unclear on the level of investigation that was performed. It is unlikely that typical facilities personnel will perform roof surveys as detailed as the ones dictated by ROOFER EMS.

BIPV roof systems appear to require little maintenance, but the systems in coastal/humid environments generally experienced mild-to-severe mold growth on the PVC membrane. Water ponding and improper water drainage significantly contributed to this problem (Figure-47). This is expected to require a major roof repair/replacement effort years from now, but prior to the end of the advertised product life, which makes the type of PVC membrane used in the BIPV system inappropriate for humid environments.

7.0 COST ASSESSMENT

7.1 COST MODEL

The life-cycle-cost elements was evaluated using the savings to investment ratio (SIR) equation,

$$SIR = \frac{(3)+(4)-(5)-(7)}{(1)-(2)}(8) \ ,$$

where the numbers refer to the cost evaluation factors in the table below. If (6) and (8) resulted in a different product life, the lower of the two values was used. Additionally, the cost of BIPV roofs were compared to that of conventional roof and rooftop PV systems. The monitoring effort is a significant portion of the project, so any costs that are not typically included in a re-roofing or PV installation project were not included in the economic analysis.

Table-11: Cost evaluation factors to consider in assessing cost/benefit of BIPV roofs.

Cost Factor	Data Tracked During the Demonstration
(1) Installation Costs of BIPV Roofs	Labor and material required to install
(2) Conventional Re-roofing Costs	Cost to re-roof using conventional roofing products
(3) A/C Operational Cost	Energy usage reduction post BIPV roof installation vs. baseline
(4) Renewable Energy Generation	System lifetime cost savings based on PV energy production
(5) PV System Maintenance/Repair	Frequency of required maintenance/repair, if any Labor and material per maintenance/repair action, if any Energy not produced due to roof or PV system maintenance
(6) PV System Lifetime	Estimate based on components degradation during demonstration
(7) Roof Maintenance/Repair	Frequency of required maintenance/repair, if any Labor and material per maintenance/repair action, if any
(8) PVC Roof Membrane System Lifetime	Estimate based on components degradation during demonstration

The installation costs of a BIPV roof included the costs for design, construction mobilization, and commissioning of the integrated roof system. Based on discussions with the manufacturer, this is the primary cost of a BIPV roof system since the expected maintenance cost is minimal. Subtracting the conventional re-roofing cost in the denominator provides the incremental cost of a BIPV roof over a conventional roof, which better represents the investment cost. The subtraction of the conventional re-roofing costs can also be considered an avoided cost.

BIPV roofs can change the building thermal envelope, which can impact the A/C energy usage. This energy usage difference should be accounted for to evaluate a BIPV roof's effect on energy efficiency. However, the data collected in this study was inconclusive due to inadequate facility conditions. Computer simulations were used to estimate the potential impact in various climates.

The BIPV roof will generate renewable energy and reduce energy purchased from the local utility, which results in cost savings. The annual energy production was recorded and the cost savings was shown for various electricity rates.

Costs associated with maintenance/repair were to be recorded when not covered by the warranty. The manufacturer claimed that only periodic washing of the roof is necessary under dirty

weather conditions. It is not DoD's facility management practice to wash roofs, so this expense was not expected to occur. However, in the event that this maintenance or repair was necessary, the cost was recorded. The measured energy production already accounts for any potential PV system downtime, so a separate analysis of that component is unnecessary. Impacts to PV efficiency were also automatically captured from the energy output measurements.

The PVC roof membrane system has a 20-year warranty, but this may be difficult to attain. Most DoD installations do not have a roof maintenance program in place, but since the roof requires minimal-to-no maintenance and some existing single-ply roof membranes have exceeded their advertised lifetime, it is possible that the BIPV roof can meet its 20 year product life. Experienced Navy roof surveyors independently projected the potential lifetime of the roof.

7.2 COST DRIVERS

The existing roof condition can be a significant cost driver. The roof repairs required for the Site II (NAS Patuxent River) BIPV roof made up nine percent of the total installation cost. The roof at Site III (MCAS Yuma) was in decent condition, which allowed for the BIPV roof be installed on top of the existing roof and did not result in any noticeable cost increase.

Economy of scale can also affect the cost and were studied on a per Watt and per square foot basis. A sales representative stated that the system becomes very cost effective for roofs exceeding 200,000 sq. ft. in size. On small-scale systems, such as Sites II and III, the installation cost of a BIPV roof was highly affected by the size of the PV system because of the high expense of the PV modules. Site II (NAS Patuxent River) costs $13.50/W or $22.70/sq. ft. when including the cost of roof repair. Without the roof repair, the cost is $12.30/W or $20.80/sq. ft. Site III (MCAS Yuma) costs $12.30/W or $27.40/sq. ft., not including the utility rebate for the PV. Since the BIPV manufacturer was located in Los Angeles, the costs were slightly affected by the distance from the manufacturing plant, but the roof at Site II (NAS Patuxent River) is 73% larger than the roof at Site III (MCAS Yuma) and has a larger, though proportionally smaller PV component, which helps explain why the two cost benchmarks for the two sites do not provide a simple way to accurately estimate the installation cost. Exact cost data is not available from the non-ESTCP BIPV roof sites, but data for some locations were available from press releases. The largest known rooftop system was a $13M, 2 MW system that consists of two roofs with a combined roof area of 640,000 sq. ft. That system costs $6.50/W or $20.31/sq. ft. Quantitatively, the proportion of the PV component of the 2 MW system yields an installed capacity of 3.1 W/sq. ft., whereas Site I (Luke AFB) is 2.6 W/sq. ft., Site II (NAS Patuxent River) is 1.7 W/sq. ft., and Site III (MCAS Yuma) is 2.2 W/sq. ft. The proportionally larger PV component is likely to have further helped reduce the cost. Note that the proportion of the PV component at the ESTCP-funded sites were primarily limited by funding, but the distribution of area covered by the PV modules at those sites were chosen to enable a better study of the BIPV system.

Solar PV incentive programs are a significant cost driver because available incentives can significantly reduce the cost of a PV system. There is currently a federal incentive, called the Business Energy Investment Tax Credit (ITC) that allows a corporate owner of a solar energy system to claim a credit on their tax filing valued at 30% of the installed cost of the solar PV system. The ESTCP-funded systems are government-owned, so this study did not qualify for the ITC. However, this study was able to make use of the Arizona Public Service (APS) utility rebate program for Site III (MCAS Yuma), which reduced the cost of the BIPV system by 17 %. It is worth noting that the APS PV rebate program at that time did not differentiate between thin

film PV and crystalline PV modules, specifically the aspect that thin film PV power output is less impacted by the incident angle of solar radiation than crystalline PV. Therefore, APS reduced the rebate amount by almost 14% because half of the low-slope roof faced north. Another significant consideration about incentives is the change of terms over time. The PV rebate for Site III (MCAS Yuma) was $2.50/W in 2008 and was reduced to $0.60/W for grid-tied, non-residential PV systems up to 30 kW by 2012.

7.3 COST ANALYSIS AND COMPARISON

Based on press releases, the installed cost without incentives originated at around $20/W and steadily decreased to $12.30/W, which is the cost benchmark generated from this study based on the prices paid in 2008. With the lowest reported installed cost at $6.50/W, it is conceivable that the cost could steadily decline to that price point for small-scale systems over time.

Earlier in this section, only the incremental cost and benefit of a BIPV system was evaluated. For those that have decided on a rooftop PV system, a more useful comparison would be between a BIPV system and a conventional roof with a conventional rooftop-mounted PV system. While the size and cost of the roof and PV system can both vary, the comparison is further complicated by the variety of commercially available, PV products. Statistical data was used to address this issue. A National Renewable Energy Laboratory (NREL) report states that the installed cost of commercial rooftop PV systems in 2010 dollars is roughly $4-$4.60 per Watt (DC) [3]. The State of California's Solar Statistics website (www.californiasolarstatistics.ca.gov) shows that the 2012 installed cost average of non-residential systems is roughly $4-$7.50 per Watt (DC) (Figure-24). The data does not make a distinction between ground and roof mounted systems, but

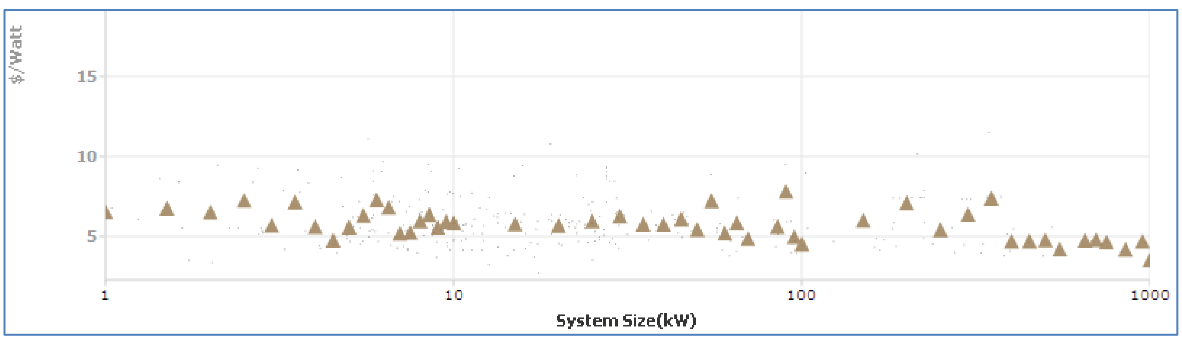

Figure-24: California Solar Statistics 2012 data showing the installed cost of non-residential PV systems vs. system size.

it is generally common for utility-scale systems be to ground mounted, so the cost range will be assumed to be representative of commercial, roof-mounted PV systems. Also, since it has only been two years from 2010 as of the start of the analysis in this report and inflation has not changed significantly, it will be assumed that the range from the NREL data is still accurate in 2012 dollars. Therefore, the range that will be used for the comparison in this report will be $4-$7.50 per Watt. Additionally, to simplify the comparison, the same roof and PV system sizes from this study will be used. Table-12 shows how the actual BIPV roof costs compare against the estimated 2012 costs. Note that comparisons do not account for market conditions at the time those BIPV roofs contracts were awarded. The installation of the BIPV roof at Site I (Luke AFB) started in 2005, which was when the product was still relatively new and conventional PV systems using rigid PV modules were still more costly. The 2007 California Solar Statistics average installed cost in present value (i.e., adjusted for inflation) is closer to $7-$10 per Watt.

Unfortunately, that website lacks data for systems prior to 2007. For a more accurate comparison, the contract for the installation of the BIPV roofs at Site II (NAS Patuxent River) and Site III (MCAS Yuma) was awarded in 2008 and the California Solar Statistics website shows the average installed cost in 2008 dollars to be roughly $7.5-$10 per Watt.

Table-12: Actual BIPV roof costs compared to estimated 2012 capital costs for conventional roofs and PV systems.

	BIPV Cost at time of Award	Conventional Roof @ $5/sq.ft. and PV @ $4/W	Conventional Roof @ $5/sq.ft. and PV @ $7.5/W	Conventional Roof @ $20/sq.ft. and PV @ $4/W	Conventional Roof @ $20/sq.ft. and PV @ $7.5/W
Site I (Luke AFB)	$6M	$2.2M	$3.5M	$4.4M	$5.7M
Site II (Patuxent River)	$363K w/ roof repairs; $332K w/o	$188K	$282K	$428K	$522K
Site III (MCAS Yuma)	$254K w/o rebate	$129K	$201K	$268K	$340K

While the capital cost analysis shows that the BIPV roof could be competitive, the operations and maintenance cost and service life also need to be considered. Conventional rooftop PV systems have a much longer history than BIPV roofs so their longevity is better understood. Both BIPV and conventional PV systems utilize the same inverters and both the PV modules have similar warranty periods, so these factors can be eliminated from the comparison. The remaining primary component is the roofing system and the PV attachment mechanism. Adhesive issues and mold growth can make this form of BIPV roof unlikely to reach its advertised 20-year life.

Site I (Luke AFB) was installed in 2006 via an ESPC, so the exact installation cost for the BIPV roof is not entirely separable from other costs, such as shared overhead costs, in that contract. Press releases reported that the system cost $6 million. HVAC operational costs were not studied for this site. The latest electricity rate for this site is unavailable, but NREL's PV Watts program reports the state average to be $0.085/kWh, which results in an estimated annual savings of $56,217. PV system repairs were performed to address the PV adhesion problem, but the effort was covered by the warranty, so it is unclear what it cost to perform the work. Since the government did not have to expend funds to perform the repair work, the repair costs are considered zero. As long as the PV modules are not significantly displaced from their original locations, the modules should continue to generate power as intended, so it will be assumed that the PV system will continue to perform to the BIPV roof's advertised 20-year life. A one-time PV inverter replacement is assumed at a total cost of $0.75/W. Maintenance on the PVC roof membrane was not performed and appeared to remain in good condition, so it will be assumed that this component will also achieve its advertised system life. Note that ROOFER EMS results predicted the BIPV roof life to be 11-19 years. The reason for the range is because the roof is so large that the assessment was separated into four sections. The simplified (i.e., escalation and inflation rates are ignored) formula for calculating the SIR provides results ranging from 0.16 to 0.27 when using the avoided conventional re-roofing cost range of $5-$20 per sq. ft. Even when making optimistic assumptions, the BIPV system is not a cost effective investment. Fortunately, installations costs have been reduced since the installation of Site I (Luke AFB).

Site II (NAS Patuxent River) was installed in 2009 and cost $363,187, with $31,151 of that associated with necessary roof removal and repairs to support the BIPV roof. The HVAC system

was not studied for this site. The reported FY10 blended electricity rate is $0.127 per kWh, resulting in an annual cost savings of $3,796. No PV maintenance or repair was needed during the study period. Roof maintenance was not performed. The 2011 ROOFER assessment projected that the roof will only last until 2013 if left alone and until 2020 if repairs are made. The estimated cost for repairs is $20,933. If we assume that the repairs will be made and the roof performs to 2020, the SIR values are estimated to be 0.074 to 0.48 depending on the avoided conventional re-roofing cost. With this 11 year system life, there is little concern about including the PV inverter replacement cost in the calculation. However, note that the 2013 date does not imply that the roof will fail for certain. It is an indication that the roof needs to be regularly surveyed because of the potential for significant failure. If repairs are not needed and the system lasts 11 years, the SIR range improves to 0.15-0.97. For an ideal 20 year system, and an assumed one-time PV inverter replacement at $0.75/W, the SIR range would be 0.20-1.29.

The installed cost for Site III (MCAS Yuma) was $253,945 when not including the $44,000 rebate. The $5-$20 per sq. ft. conventional re-roofing cost range also applies here. The HVAC impact is assumed to be zero for this particular facility because of the inconclusive results. The reported FY10 blended electricity rate is $0.073/kWh, resulting in an annual cost savings of $2,470. No PV maintenance or repair was needed during the study period and no degradation of the PV modules or adhesive was observed. No roof maintenance or repair was needed and the PVC membrane appeared to be in good condition. The 2011 ROOFER results predicted a total system life of 18 years after an estimated repair effort of $1,072. However, as stated earlier, this does not imply that the roof will fail at that time. The following table shows the SIR values for the various scenarios. All assume a one-time PV inverter replacement at a cost of $0.75/W. Note that the SIR values for the scenarios with HVAC savings assume that there is good thermal coupling between the roof and conditioned space, which means that the estimated savings of 9.89 kWh/m^2 from section 6.5 was used. In other words, the SIR values for the scenarios with HVAC savings reflects a similar, but theoretical facility with a tighter building envelope located in Phoenix, AZ.

Table-13: SIR values of various scenarios based on the Site III (MCAS Yuma) BIPV roof.

System Life	SIR with Avoided Re-roof at $5/sq.ft.	SIR with Avoided Re-roof at $20/sq.ft.	SIR with Avoided Re-roof at $5/sq.ft. & Rebates	SIR with Avoided Re-roof at $20/sq.ft. & Rebates	SIR with Avoided Re-roof at $5/sq.ft. & HVAC Savings	SIR with Avoided Re-roof at $20/sq.ft. & HVAC Savings	SIR with Avoided Re-roof at $5/sq.ft. & HVAC Savings & Rebate	SIR with Avoided Re-roof at $20/sq.ft. & HVAC Savings & Rebate
15-Year	0.10	0.30	0.13	0.84	0.14	0.44	0.18	1.22
20-Year	0.16	0.48	0.20	1.34	0.22	0.66	0.28	1.85

8.0 IMPLEMENTATION ISSUES

BIPV roof technology and products are still relatively new, so there is a general lack of experience and history with BIPV roofs throughout DoD and even in the private industry. Lessons were learned from the installation and the real world effects on the BIPV roof. Some issues could now be overcome with better practices, whereas other problems were inherent to the roof's components and did not become apparent until a time after installation was completed.

DON typically utilize construction expertise within the Facilities and Engineering Acquisition Division (FEAD) and Resident Officer in Charge of Construction (ROICC) offices to perform quality assurance during construction efforts. The Army and Air Force utilize similar services. Before the installation of one BIPV roof, personnel had expressed their need to learn about the BIPV roof system in order to properly review contractor work. It is recommended that DoD personnel in charge of rooftop solar projects, at minimum, consult with a DoD roofing specialist. Ideally, personnel experienced with rooftop solar projects would provide training and/or consultation prior to design and construction phases for each DoD BIPV roof project.

There was a lack of firefighter safety standards and design practices that reduce hazards in the event of a fire. For example, this type of BIPV roof system has the electric conduit embedded in the insulation layer. The hidden cables present electric hazards to firefighters because PV modules continue to function even when disconnected from the facility. Some industry standards like the National Electric Code address fire and electrical safety of PV systems, but the rooftop PV industry is still relatively new and as new technologies may require revised guidelines. The Underwriter Laboratories report on *Firefighter Safety and Photovoltaic Installations Research Project* and the California Department of Forestry and Fire Protection *Solar Photovoltaic Installation Guideline* are recommended and are free for download from the internet.

For the BIPV roofs funded by ESTCP, the contractor designed the BIPV system and Navy personnel reviewed the submittals using the information available prior to this study. The two notable issues that could have been prevented had the results of this study been available include the flashing and the vapor barrier. The most straightforward solution is to establish minimum flashing height requirements explicitly in the statement of work to ensure that objects, such as air vents, have their height raised to meet the requirement. This issue is more likely to occur when using a BIPV roof overlay approach, but can still occur in roof replacement efforts when the new insulation thickness is greater than the original insulation thickness. It is worth noting that the insufficient flashing issue has been seen in regular roofing renovation projects as well. With respect to the vapor barrier, the missing component caused a roof deck to warp because of the humidity and frequent rainfall in that location. The warping was not evident until months after the system was installed and was not considered because the prior roof, a modified bitumen system, did not require one. Though, this problem was not observed in other BIPV roofs in other humid/wet locations surveyed during the course of this study, future systems should ensure that a vapor barrier be included in the statement of work if a vapor barrier does not exist.

Mold growth appeared in many of the larger systems because either the climate was humid, causing the roof to remain generally wet for a long period of time, and/or there was insufficient drainage, causing water to form small ponds. While mold growth on PVC roof membranes are tested under an ASTM standard and certain mold may not be malignant to roof longevity, the energy efficiency benefits are greatly reduced due to the reduction in roof reflectivity, which can negatively impact the economic benefits. Personnel in charge of specifying roof requirements

should ensure that both the workmanship and manufacturer warranties provide resolutions regarding both mold growth and improper roof drainage. Insufficient drainage can be a result of a poor design and/or a poor installer. In the case of a BIPV retrofit, it is possible that the original roof was never properly designed or installed. A properly timed survey within a day or two after a rain event of the existing roof will help identify drainage issues and areas for improvement when the BIPV roof is installed. In addition a BIPV roof assessment prior to the expiration of the workmanship warranty is recommended.

In two of the systems surveyed, the PV adhesive failed. While the system integrator attempted to fix this issue, the results were unfavorable and the tape solution itself generated undesirable conditions, such as water retention and a sticky residue. The manufacturer removed PVC membrane from their list of approved substrates and instead standardized on TPO membranes for this type of BIPV system after this study started. However, both the system integrator and the PVL manufacturer filed for bankruptcy in 2012 and are no longer able to service the BIPV roof, but there is still at least one third-party vendor who has access to some unused PVLs. The PVC membrane manufacturer is still in business and third-party solutions are available to address the adhesive issue, but may void the remaining warranty on the PVC membrane, so the PVC membrane manufacturer should be engaged before proceeding with a repair effort.

When the PV adhesive fails, it is possible to remove the affected PVLs or a group of PVLs on the same carrier sheet. Removing an individual PVL may leave adhesive residue that is difficult to remove and a clean PVC membrane surface is necessary if a replacement PVL is desired. Replacing individual PVLs is not recommended because there is no guarantee/warranty that the new PVL will not experience the same adhesive failure and there has not been much research into finding a reliable adhesive for adhering PV to the PVC membrane. If the PVL is removed, but not replaced, then the carrier sheet will need to be patched with additional PVC membrane material to ensure water does not flow to the other PVLs or into the roof. The patching of a PVC membrane utilizes a no-flame, heat welding approach and is a standard roofing industry task so the PVC membrane warranty could be maintained as long as the PVC manufacturer’s requirements are met. Removing a group of PVLs on the same carrier sheet requires cutting into the carrier sheet and disconnecting the BIPV panel. If replacement PVLs are undesired, then the roof can be patched with a new PVC sheet slightly larger than the carrier sheet that was removed. If replacing the PVLs, the BIPV system owner should consider the use of a TPO membrane as the carrier sheet. While TPO can not be heat welded to PVC, mechanical fasteners will likely be necessary and the actual approach will be left to the third-party solution provider. However, it is unknown whether or not this approach will void the PVC membrane warranty, so the PVC roof membrane manufacturer should be consulted prior to starting this repair effort. Regardless of the approach, when one or more PVLs are removed or replaced, an electrical engineer or a PV designer should be consulted to determine how the change may impact the system’s electrical performance and identify any mitigation techniques.

A UFGS was to be developed if this system performed successfully, but due to the various issues and the bankruptcy of the PV and systems integrator, a specification would not help with the adoption of this technology. In addition, the emergence of new CIGS and CdTe PV modules and vendors have led to a much more diverse group of designs since this study started and it is not possible to simply write one guide specification to address these new and varied options. Instead it is recommended that the lessons learned from this study be applied to the acquisition planning, design, and construction process.

The technical areas of concerns may be mitigated in various ways depending on the acquisition vehicle used. When upfront capital is invested, such as through the Military Construction (MILCON) program, maintenance is typically not included in the cost. DoD will be responsible for maintaining and repairing the BIPV system after the warranty period is over. Therefore, the acquisition workforce needs to be careful with the solicitation requirements and fully understand the details of the workmanship and manufacturer warranty associated with the proposal. When a financed, performance contract is used, such as an Energy Savings Performance Contract (ESPC), maintenance of the system may be included in the contract. In addition, risks associated with BIPV system ownership can be mitigated by adequately addressing the performance requirements that the energy service company must meet in order to comply with the contract. In the case of an ESPC, the Measurement & Verification (M&V) plan is the core to performance measurement and, in general, the more thorough the M&V plan, the more expensive the effort, but results in a lower risk to the government. In addition, the energy service company will need to be comfortable with guaranteeing the performance of BIPV roofs or else another rooftop PV system may be proposed instead. Risk management will need to be applied by both the government and contractor to find the best balance for the project. A third, more radical and more complex method of acquiring BIPV roofs would be to utilize an approach similar to how the large PV arrays were installed at Nellis AFB and NAWCWD China Lake which are similar in concept to an Enhanced Use Lease (EUL) in conjunction with a Power Purchase Agreement (PPA). An EUL can be used to lease out roofs as real estate. While this does not preclude the lessee to do something else with the roof space, its uses are extremely limited. Also, as it was with an ESPC, the lessee will need to be comfortable with BIPV roofs or it will propose a different rooftop PV system. A PPA is used to purchase the power. Standard EUL and PPA require full and open competition and they may have different contract durations, which adds to the complexity. However, if achieved, the lessee will own and operate the roofs and PV systems and eliminates most, if not all, of the risks to DoD.

The exact BIPV system studied is no longer commercially available, but adhered PV systems are still in use and the lessons learned from this study can also be applied to other rooftop systems that use an adhered PV approach as they can experience similar issues. Risks associated with BIPV systems can be mitigated by applying sound roofing practices, being aware of potential failure points, and utilizing the proper acquisition vehicle. It is recommended that DoD revisit the BIPV roofs in this study several years from now, maintain a list of adhered PV systems, identify their basic PV and roof components, and survey a sample set every few years to identify performance and durability trends of the different components.

9.0 REFERENCES

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Appendix A
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